Breadth-first search
COMS20010 (Algorithms II)

John Lapinskas, University of Bristol

Shortest path-finding

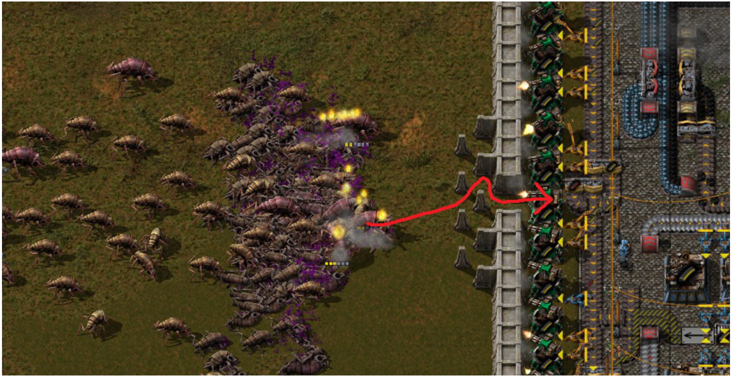
Last time: Given a graph G and two vertices $x, y \in V(G)$, is there a path from x to y?

E.g. can an enemy attack the base without breaking down a wall?

Shortest path-finding

Last time: Given a graph G and two vertices $x, y \in V(G)$, is there a path from x to y?

E.g. can an enemy attack the base without breaking down a wall?



This time: What is the **shortest** path from x to y?

Graph distance

This time: What is the **shortest** path from x to y?

What do we mean by "shortest"?

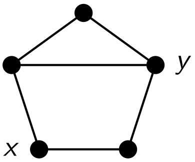
The **distance** between x and y, $\boldsymbol{d(x, y)}$, is the length in edges of a shortest path between x and y, or ∞ if no such path exists.

Graph distance

This time: What is the **shortest** path from x to y?

What do we mean by "shortest"?

The **distance** between x and y, $\boldsymbol{d(x,y)}$, is the length in edges of a shortest path between x and y, or ∞ if no such path exists.

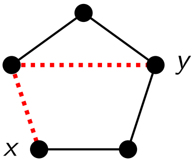


Graph distance

This time: What is the **shortest** path from x to y?

What do we mean by "shortest"?

The **distance** between x and y, $\boldsymbol{d(x,y)}$, is the length in edges of a shortest path between x and y, or ∞ if no such path exists.



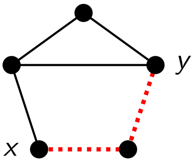
$d(x,y) = 2$

Graph distance

This time: What is the **shortest** path from x to y?

What do we mean by "shortest"?

The **distance** between x and y, $\boldsymbol{d(x,y)}$, is the length in edges of a shortest path between x and y, or ∞ if no such path exists.



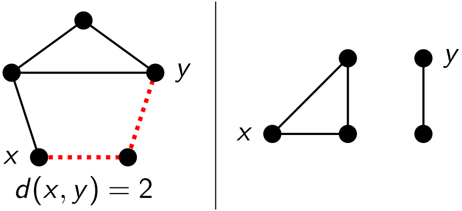
$d(x,y) = 2$

Graph distance

This time: What is the **shortest** path from x to y?

What do we mean by "shortest"?

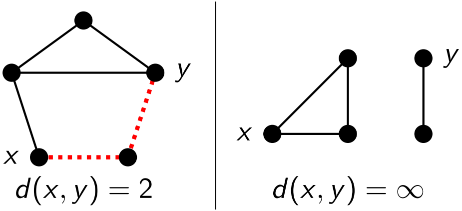
The **distance** between x and y, $\boldsymbol{d(x,y)}$, is the length in edges of a shortest path between x and y, or ∞ if no such path exists.



This time: What is the **shortest** path from x to y?

What do we mean by “shortest”?

The **distance** between x and y, $\boldsymbol{d(x,y)}$, is the length in edges of a shortest path between x and y, or ∞ if no such path exists.

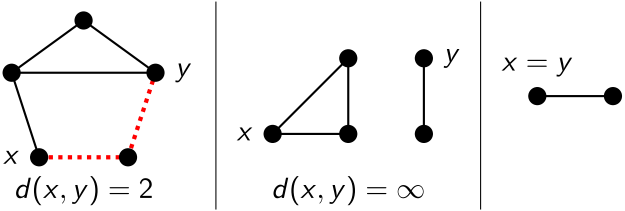


Graph distance

This time: What is the **shortest** path from x to y?

What do we mean by "shortest"?

The **distance** between x and y, $\boldsymbol{d(x, y)}$, is the length in edges of a shortest path between x and y, or ∞ if no such path exists.

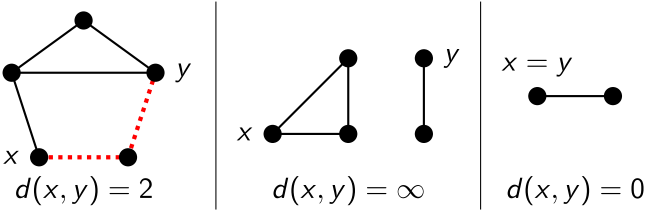


Graph distance

This time: What is the **shortest** path from x to y?

What do we mean by "shortest"?

The **distance** between x and y, $\boldsymbol{d(x,y)}$, is the length in edges of a shortest path between x and y, or ∞ if no such path exists.

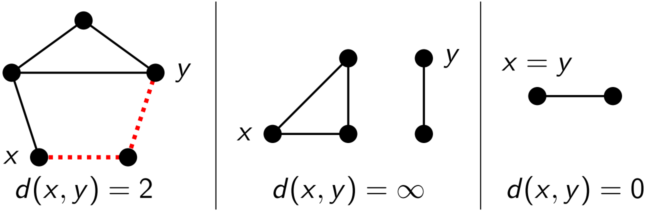


Graph distance

This time: What is the **shortest** path from x to y?

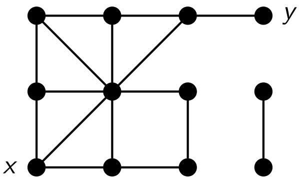
What do we mean by "shortest"?

The **distance** between x and y, $\boldsymbol{d(x,y)}$, is the length in edges of a shortest path between x and y, or ∞ if no such path exists.



In directed graphs, it's the same except that the path is **from** x **to** y.
So... we might not have $d(x,y) = d(y,x)$!

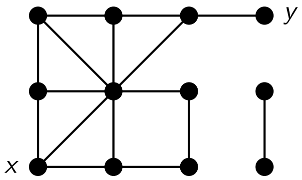
Input: A graph G and two vertices x and y.
Output: A shortest path from x to y.



Let L_i be the set of vertices at distance i from x.

Breadth-first search: The idea

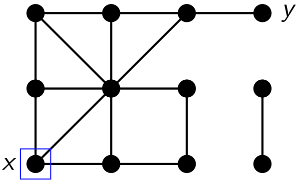
Input: A graph G and two vertices x and y.
Output: A shortest path from x to y.



Let L_i be the set of vertices at distance i from x. So $L_0 = \{x\}$.

Breadth-first search: The idea

Input: A graph G and two vertices x and y.
Output: A shortest path from x to y.

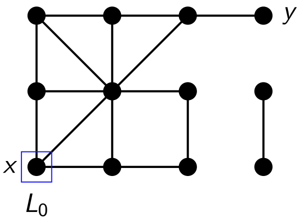


L_0

Let L_i be the set of vertices at distance i from x. So $L_0 = \{x\}$.

Breadth-first search: The idea

Input: A graph G and two vertices x and y.
Output: A shortest path from x to y.

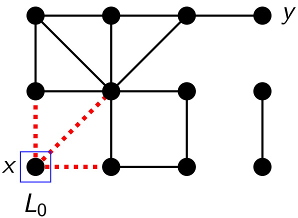


Let L_i be the set of vertices at distance i from x. So $L_0 = \{x\}$.

L_1 is everything adjacent to x.

Breadth-first search: The idea

Input: A graph G and two vertices x and y.
Output: A shortest path from x to y.

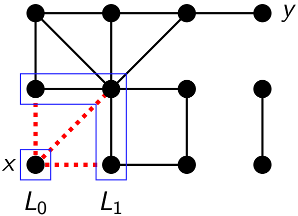


Let L_i be the set of vertices at distance i from x. So $L_0 = \{x\}$.

L_1 is everything adjacent to x.

Breadth-first search: The idea

Input: A graph G and two vertices x and y.
Output: A shortest path from x to y.

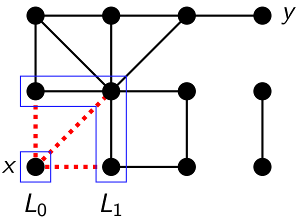


Let L_i be the set of vertices at distance i from x. So $L_0 = \{x\}$.

L_1 is everything adjacent to x.

Breadth-first search: The idea

Input: A graph G and two vertices x and y.
Output: A shortest path from x to y.



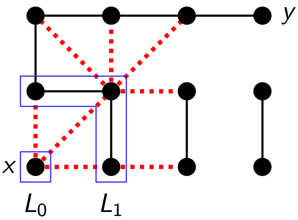
Let L_i be the set of vertices at distance i from x. So $L_0 = \{x\}$.

L_1 is everything adjacent to x.

L_2 is everything adjacent to L_1, but **not** in L_0 or L_1.

Breadth-first search: The idea

Input: A graph G and two vertices x and y.
Output: A shortest path from x to y.



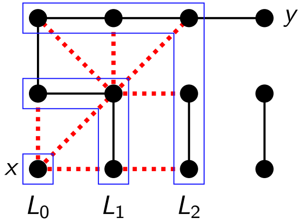
Let L_i be the set of vertices at distance i from x. So $L_0 = \{x\}$.

L_1 is everything adjacent to x.

L_2 is everything adjacent to L_1, but **not** in L_0 or L_1.

Breadth-first search: The idea

Input: A graph G and two vertices x and y.
Output: A shortest path from x to y.



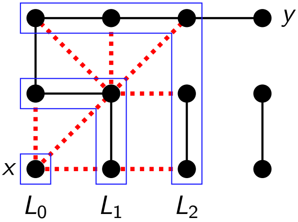
Let L_i be the set of vertices at distance i from x. So $L_0 = \{x\}$.

L_1 is everything adjacent to x.

L_2 is everything adjacent to L_1, but **not** in L_0 or L_1.

Breadth-first search: The idea

Input: A graph G and two vertices x and y.
Output: A shortest path from x to y.



Let L_i be the set of vertices at distance i from x. So $L_0 = \{x\}$.

L_1 is everything adjacent to x.

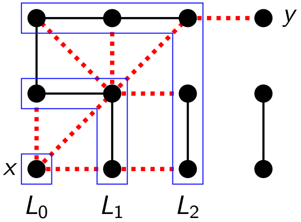
L_2 is everything adjacent to L_1, but **not** in L_0 or L_1.

In general, L_{i+1} is everything adjacent to L_i and not in $L_0 \cup \cdots \cup L_i$.

By continuing this until we find y, keeping track of which edges we use, we get a shortest path to y.

Breadth-first search: The idea

Input: A graph G and two vertices x and y.
Output: A shortest path from x to y.



Let L_i be the set of vertices at distance i from x. So $L_0 = \{x\}$.

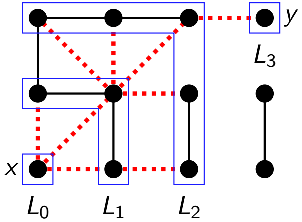
L_1 is everything adjacent to x.

L_2 is everything adjacent to L_1, but **not** in L_0 or L_1.

In general, L_{i+1} is everything adjacent to L_i and not in $L_0 \cup \cdots \cup L_i$.

By continuing this until we find y, keeping track of which edges we use, we get a shortest path to y.

Input: A graph G and two vertices x and y.
Output: A shortest path from x to y.



Let L_i be the set of vertices at distance i from x. So $L_0 = \{x\}$.

L_1 is everything adjacent to x.

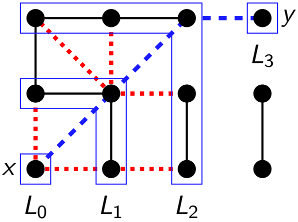
L_2 is everything adjacent to L_1, but **not** in L_0 or L_1.

In general, L_{i+1} is everything adjacent to L_i and not in $L_0 \cup \cdots \cup L_i$.

By continuing this until we find y, keeping track of which edges we use, we get a shortest path to y.

Breadth-first search: The idea

Input: A graph G and two vertices x and y.
Output: A shortest path from x to y.



Let L_i be the set of vertices at distance i from x. So $L_0 = \{x\}$.

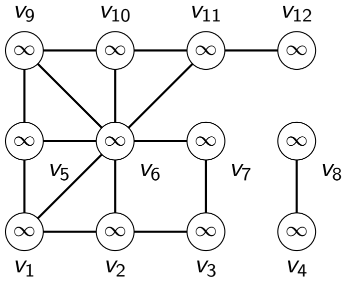
L_1 is everything adjacent to x.

L_2 is everything adjacent to L_1, but **not** in L_0 or L_1.

In general, L_{i+1} is everything adjacent to L_i and not in $L_0 \cup \cdots \cup L_i$.

By continuing this until we find y, keeping track of which edges we use, we get a shortest path to y.

Breadth-first search: Implementation

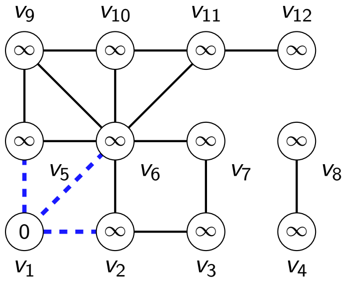


`queue:`

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \dots, v_n$.
Let $\texttt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\texttt{L}[1] \leftarrow 0$, $\texttt{pred}[1] \leftarrow \texttt{None}$.
Let `queue` be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while `queue` *is not empty* **do**
    Remove front tuple (v_i, v_j) from `queue`.
    if $\texttt{L}[j] = \infty$ **then**
        Add (v_j, v_k) to `queue` for all $\{v_j, v_k\} \in E$, $k \neq i$.
        Set $\texttt{L}[j] \leftarrow \texttt{L}[i] + 1$, $\texttt{pred}[j] = i$.
Return `L` and `pred`.



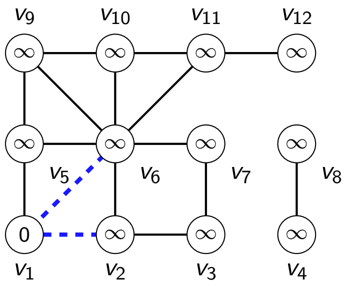
$\texttt{queue}: (1,5), (1,6), (1,2)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \ldots, v_n$.
Let $\texttt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\texttt{L}[1] \leftarrow 0$, $\texttt{pred}[1] \leftarrow \texttt{None}$.
Let $\texttt{queue}$ be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while $\texttt{queue}$ *is not empty* **do**
    Remove front tuple (v_i, v_j) from $\texttt{queue}$.
    if $\texttt{L}[j] = \infty$ **then**
        Add (v_j, v_k) to $\texttt{queue}$ for all $\{v_j, v_k\} \in E$, $k \neq i$.
        Set $\texttt{L}[j] \leftarrow \texttt{L}[i] + 1$, $\texttt{pred}[j] = i$.
Return $\texttt{L}$ and $\texttt{pred}$.

Breadth-first search: Implementation



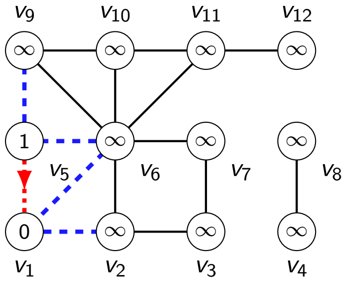
$\texttt{queue}: (1,6), (1,2)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \ldots, v_n$.
Let $\texttt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\texttt{L}[1] \leftarrow 0$, $\texttt{pred}[1] \leftarrow \texttt{None}$.
Let $\texttt{queue}$ be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while $\texttt{queue}$ *is not empty* **do**
  Remove front tuple (v_i, v_j) from $\texttt{queue}$.
  if $\texttt{L}[j] = \infty$ **then**
    Add (v_j, v_k) to $\texttt{queue}$ for all $\{v_j, v_k\} \in E$, $k \neq i$.
    Set $\texttt{L}[j] \leftarrow \texttt{L}[i] + 1$, $\texttt{pred}[j] = i$.
Return $\texttt{L}$ and $\texttt{pred}$.

Breadth-first search: Implementation



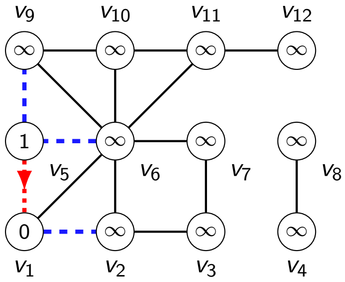
queue: $(1,6),(1,2),(5,9),(5,6)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \dots, v_n$.
Let $\texttt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\texttt{L}[1] \leftarrow 0$, $\texttt{pred}[1] \leftarrow \texttt{None}$.
Let `queue` be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while `queue` *is not empty* **do**
    Remove front tuple (v_i, v_j) from `queue`.
    if $\texttt{L}[j] = \infty$ **then**
        Add (v_j, v_k) to `queue` for all $\{v_j, v_k\} \in E$, $k \neq i$.
        Set $\texttt{L}[j] \leftarrow \texttt{L}[i] + 1$, $\texttt{pred}[j] = i$.
Return `L` and `pred`.

Breadth-first search: Implementation



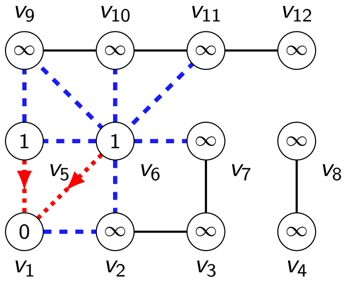
$\mathrm{queue}: (1,2), (5,9), (5,6)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

```
Number the vertices of G as v = v_1, ..., v_n.
Let L[i] ← ∞ for all i ∈ [n].
Let L[1] ← 0, pred[1] ← None.
Let queue be a queue containing all tuples
  (v, v_j) with {v, v_j} ∈ E.
while queue is not empty do
    Remove front tuple (v_i, v_j) from queue.
    if L[j] = ∞ then
        Add (v_j, v_k) to queue for all
          {v_j, v_k} ∈ E, k ≠ i.
        Set L[j] ← L[i] + 1, pred[j] = i.
Return L and pred.
```

Breadth-first search: Implementation

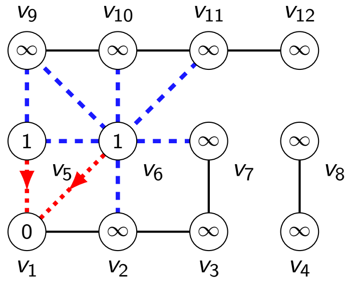


queue: $(1,2),(5,9),(5,6),(6,5),$
$(6,9),(6,10),(6,11),(6,7),$
$(6,2)$

Algorithm: BFS

Input : Graph $G=(V,E)$, vertex $v \in V$.
Output : $d(v,y)$ for all $y \in V$ and "a way of finding shortest paths".

```
Number the vertices of G as v = v_1, ..., v_n.
Let L[i] ← ∞ for all i ∈ [n].
Let L[1] ← 0, pred[1] ← None.
Let queue be a queue containing all tuples
  (v, v_j) with {v, v_j} ∈ E.
while queue is not empty do
    Remove front tuple (v_i, v_j) from queue.
    if L[j] = ∞ then
        Add (v_j, v_k) to queue for all
          {v_j, v_k} ∈ E, k ≠ i.
        Set L[j] ← L[i] + 1, pred[j] = i.
Return L and pred.
```

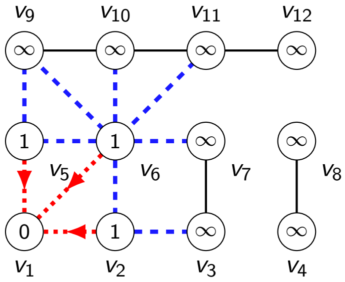


queue : $(5,9),(5,6),(6,5),(6,9),$
$(6,10),(6,11),(6,7),(6,2),$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \ldots, v_n$.
Let $\texttt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\texttt{L}[1] \leftarrow 0$, $\texttt{pred}[1] \leftarrow \texttt{None}$.
Let queue be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while queue *is not empty* **do**
    Remove front tuple (v_i, v_j) from queue.
    if $\texttt{L}[j] = \infty$ **then**
        Add (v_j, v_k) to queue for all $\{v_j, v_k\} \in E$, $k \neq i$.
        Set $\texttt{L}[j] \leftarrow \texttt{L}[i] + 1$, $\texttt{pred}[j] = i$.
Return L and pred.



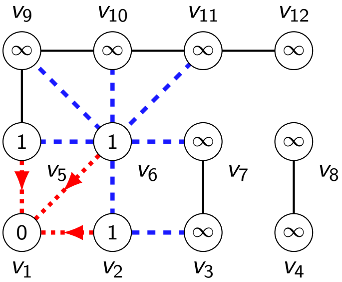
queue : $(5,9),(5,6),(6,5),(6,9),$
$(6,10),(6,11),(6,7),(6,2),$
$(2,6),(2,3)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \dots, v_n$.
Let $\texttt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\texttt{L}[1] \leftarrow 0$, $\texttt{pred}[1] \leftarrow \texttt{None}$.
Let queue be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while queue *is not empty* **do**
  Remove front tuple (v_i, v_j) from queue.
  if $\texttt{L}[j] = \infty$ **then**
    Add (v_j, v_k) to queue for all $\{v_j, v_k\} \in E$, $k \neq i$.
    Set $\texttt{L}[j] \leftarrow \texttt{L}[i] + 1$, $\texttt{pred}[j] = i$.
Return L and pred.

Breadth-first search: Implementation

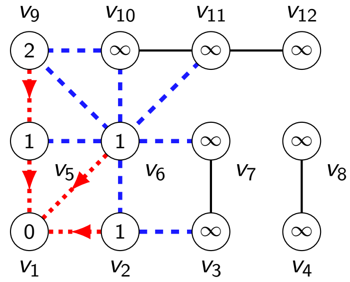


queue : $(5,6),(6,5),(6,9),(6,10),$
$(6,11),(6,7),(6,2),(2,6),$
$(2,3)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \dots, v_n$.
Let $\mathtt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\mathtt{L}[1] \leftarrow 0$, $\mathtt{pred}[1] \leftarrow \mathtt{None}$.
Let queue be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while queue *is not empty* **do**
    Remove front tuple (v_i, v_j) from queue.
    if $\mathtt{L}[j] = \infty$ **then**
        Add (v_j, v_k) to queue for all $\{v_j, v_k\} \in E$, $k \neq i$.
        Set $\mathtt{L}[j] \leftarrow \mathtt{L}[i] + 1$, $\mathtt{pred}[j] = i$.
Return L and pred.



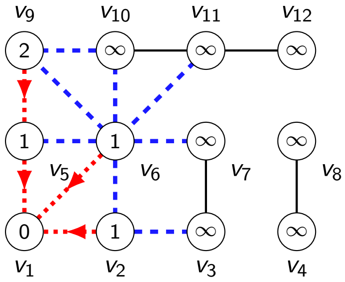
queue : $(5,6), (6,5), (6,9), (6,10),$
$(6,11), (6,7), (6,2), (2,6),$
$(2,3), (9,10), (9,6)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \dots, v_n$.
Let $\texttt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\texttt{L}[1] \leftarrow 0$, $\texttt{pred}[1] \leftarrow \texttt{None}$.
Let $\texttt{queue}$ be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while $\texttt{queue}$ *is not empty* **do**
    Remove front tuple (v_i, v_j) from $\texttt{queue}$.
    if $\texttt{L}[j] = \infty$ **then**
        Add (v_j, v_k) to $\texttt{queue}$ for all $\{v_j, v_k\} \in E$, $k \neq i$.
        Set $\texttt{L}[j] \leftarrow \texttt{L}[i] + 1$, $\texttt{pred}[j] = i$.
Return $\texttt{L}$ and $\texttt{pred}$.

Breadth-first search: Implementation



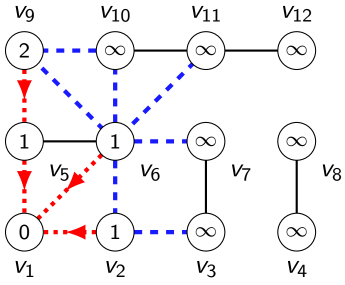
queue: $(6,5),(6,9),(6,10),(6,11),$
$(6,7),(6,2),(2,6),(2,3),$
$(9,10),(9,6)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \ldots, v_n$.
Let $\mathtt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\mathtt{L}[1] \leftarrow 0$, $\mathtt{pred}[1] \leftarrow \mathtt{None}$.
Let $\mathtt{queue}$ be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while $\mathtt{queue}$ *is not empty* **do**
  Remove front tuple (v_i, v_j) from $\mathtt{queue}$.
  if $\mathtt{L}[j] = \infty$ **then**
    Add (v_j, v_k) to $\mathtt{queue}$ for all $\{v_j, v_k\} \in E$, $k \neq i$.
    Set $\mathtt{L}[j] \leftarrow \mathtt{L}[i] + 1$, $\mathtt{pred}[j] = i$.
Return $\mathtt{L}$ and $\mathtt{pred}$.

Breadth-first search: Implementation

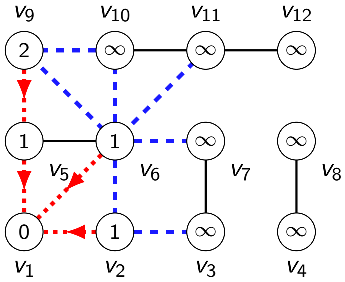


$\texttt{queue}: (6,9),(6,10),(6,11),(6,7),$
$(6,2),(2,6),(2,3),(9,10),$
$(9,6)$

Algorithm: BFS

Input : Graph $G=(V,E)$, vertex $v \in V$.
Output : $d(v,y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \dots, v_n$.
Let $\texttt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\texttt{L}[1] \leftarrow 0$, $\texttt{pred}[1] \leftarrow \texttt{None}$.
Let $\texttt{queue}$ be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while $\texttt{queue}$ *is not empty* **do**
    Remove front tuple (v_i, v_j) from $\texttt{queue}$.
    if $\texttt{L}[j] = \infty$ **then**
        Add (v_j, v_k) to $\texttt{queue}$ for all $\{v_j, v_k\} \in E$, $k \neq i$.
        Set $\texttt{L}[j] \leftarrow \texttt{L}[i] + 1$, $\texttt{pred}[j] = i$.
Return $\texttt{L}$ and $\texttt{pred}$.



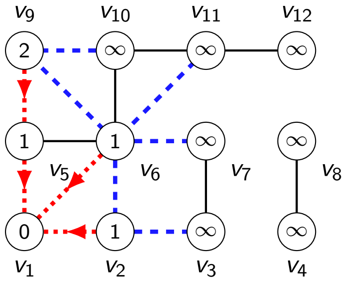
$$\texttt{queue}: (6,10),(6,11),(6,7),(6,2),\\ (2,6),(2,3),(9,10),(9,6)$$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

```
Number the vertices of G as v = v_1, ..., v_n.
Let L[i] ← ∞ for all i ∈ [n].
Let L[1] ← 0, pred[1] ← None.
Let queue be a queue containing all tuples
  (v, v_j) with {v, v_j} ∈ E.
while queue is not empty do
    Remove front tuple (v_i, v_j) from queue.
    if L[j] = ∞ then
        Add (v_j, v_k) to queue for all
          {v_j, v_k} ∈ E, k ≠ i.
        Set L[j] ← L[i] + 1, pred[j] = i.
Return L and pred.
```

Breadth-first search: Implementation



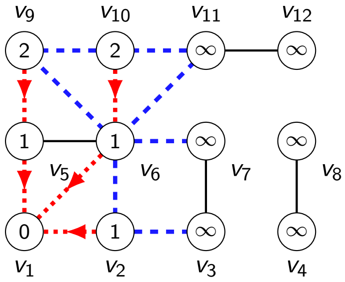
queue: $(6,11),(6,7),(6,2),(2,6),$
$(2,3),(9,10),(9,6)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \dots, v_n$.
Let $\texttt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\texttt{L}[1] \leftarrow 0$, $\texttt{pred}[1] \leftarrow$ `None`.
Let `queue` be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while `queue` *is not empty* **do**
    Remove front tuple (v_i, v_j) from `queue`.
    if $\texttt{L}[j] = \infty$ **then**
        Add (v_j, v_k) to `queue` for all $\{v_j, v_k\} \in E$, $k \neq i$.
        Set $\texttt{L}[j] \leftarrow \texttt{L}[i] + 1$, $\texttt{pred}[j] = i$.
Return `L` and `pred`.

Breadth-first search: Implementation



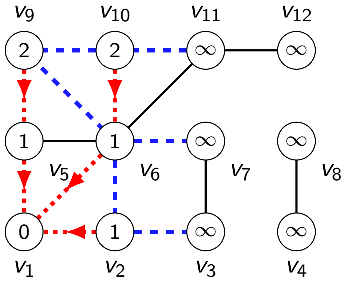
queue : $(6,11),(6,7),(6,2),(2,6),$
$(2,3),(9,10),(9,6),(10,11),$
$(10,9)$

Algorithm: BFS

Input : Graph $G=(V,E)$, vertex $v \in V$.
Output : $d(v,y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \dots, v_n$.
Let $\mathtt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\mathtt{L}[1] \leftarrow 0$, $\mathtt{pred}[1] \leftarrow \mathtt{None}$.
Let queue be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while queue *is not empty* **do**
    Remove front tuple (v_i, v_j) from queue.
    if $\mathtt{L}[j] = \infty$ **then**
        Add (v_j, v_k) to queue for all $\{v_j, v_k\} \in E$, $k \neq i$.
        Set $\mathtt{L}[j] \leftarrow \mathtt{L}[i] + 1$, $\mathtt{pred}[j] = i$.
Return L and pred.

Breadth-first search: Implementation



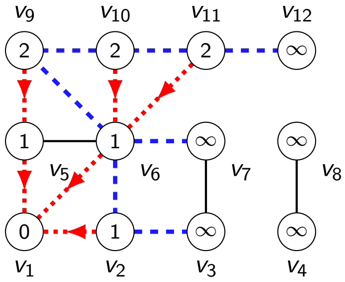
queue : $(6,7), (6,2), (2,6), (2,3),$
$(9,10), (9,6), (10,11), (10,9)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \dots, v_n$.
Let L[i] $\leftarrow \infty$ for all $i \in [n]$.
Let L[1] $\leftarrow 0$, pred[1] $\leftarrow$ None.
Let queue be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while queue *is not empty* **do**
    Remove front tuple (v_i, v_j) from queue.
    if L[j] $= \infty$ **then**
        Add (v_j, v_k) to queue for all $\{v_j, v_k\} \in E$, $k \neq i$.
        Set L[j] $\leftarrow$ L[i] $+ 1$, pred[j] $= i$.
Return L and pred.

Breadth-first search: Implementation



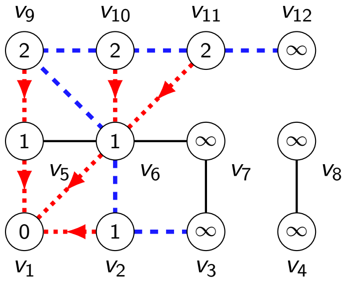
$\texttt{queue}: (6,7), (6,2), (2,6), (2,3), (9,10), (9,6), (10,11), (10,9), (11,10), (11,12)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \dots, v_n$.
Let $\texttt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\texttt{L}[1] \leftarrow 0$, $\texttt{pred}[1] \leftarrow \texttt{None}$.
Let $\texttt{queue}$ be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while $\texttt{queue}$ *is not empty* **do**
    Remove front tuple (v_i, v_j) from $\texttt{queue}$.
    if $\texttt{L}[j] = \infty$ **then**
        Add (v_j, v_k) to $\texttt{queue}$ for all $\{v_j, v_k\} \in E$, $k \neq i$.
        Set $\texttt{L}[j] \leftarrow \texttt{L}[i] + 1$, $\texttt{pred}[j] = i$.
Return $\texttt{L}$ and $\texttt{pred}$.

Breadth-first search: Implementation

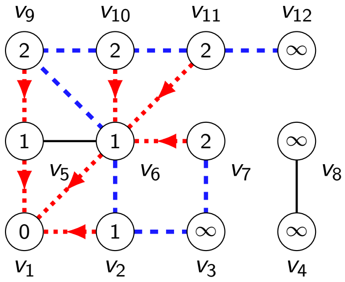


queue : $(6,2),(2,6),(2,3),(9,10),$
$(9,6),(10,11),(10,9),(11,10),$
$(11,12)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

1 Number the vertices of G as $v = v_1, \dots, v_n$.
2 Let $\mathtt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
3 Let $\mathtt{L}[1] \leftarrow 0$, $\mathtt{pred}[1] \leftarrow$ `None`.
4 Let `queue` be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
5 **while** `queue` *is not empty* **do**
6   Remove front tuple (v_i, v_j) from `queue`.
7   **if** $\mathtt{L}[j] = \infty$ **then**
8   Add (v_j, v_k) to `queue` for all $\{v_j, v_k\} \in E$, $k \neq i$.
9   Set $\mathtt{L}[j] \leftarrow \mathtt{L}[i] + 1$, $\mathtt{pred}[j] = i$.
10 Return `L` and `pred`.

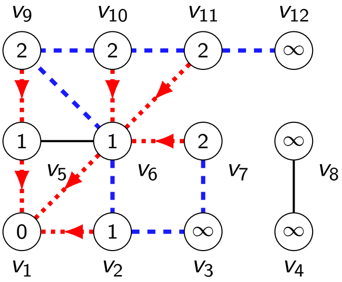


$\texttt{queue}: (6,2),(2,6),(2,3),(9,10),$
$(9,6),(10,11),(10,9),(11,10),$
$(11,12),(7,3)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

```
Number the vertices of G as v = v_1, ..., v_n.
Let L[i] ← ∞ for all i ∈ [n].
Let L[1] ← 0, pred[1] ← None.
Let queue be a queue containing all tuples
  (v, v_j) with {v, v_j} ∈ E.
while queue is not empty do
    Remove front tuple (v_i, v_j) from queue.
    if L[j] = ∞ then
        Add (v_j, v_k) to queue for all
          {v_j, v_k} ∈ E, k ≠ i.
        Set L[j] ← L[i] + 1, pred[j] = i.
Return L and pred.
```

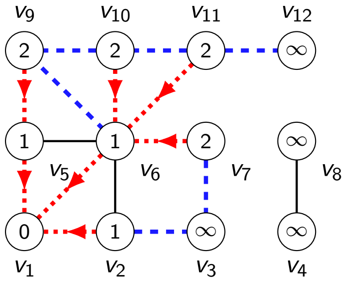


queue: $(2,6),(2,3),(9,10),(9,6),$
$(10,11),(10,9),(11,10),(11,12),$
$(7,3)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

```
Number the vertices of G as v = v_1, ..., v_n.
Let L[i] ← ∞ for all i ∈ [n].
Let L[1] ← 0, pred[1] ← None.
Let queue be a queue containing all tuples
  (v, v_j) with {v, v_j} ∈ E.
while queue is not empty do
    Remove front tuple (v_i, v_j) from queue.
    if L[j] = ∞ then
        Add (v_j, v_k) to queue for all
          {v_j, v_k} ∈ E, k ≠ i.
        Set L[j] ← L[i] + 1, pred[j] = i.
Return L and pred.
```



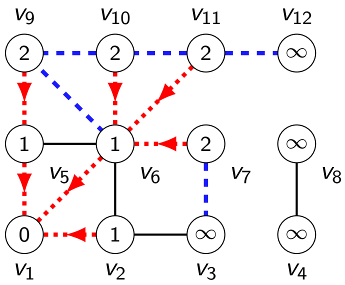
queue : $(2,3),(9,10),(9,6),(10,11),$
$(10,9),(11,10),(11,12),(7,3)$

Algorithm: BFS

Input : Graph $G=(V,E)$, vertex $v \in V$.
Output : $d(v,y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \dots, v_n$.
Let $\mathtt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\mathtt{L}[1] \leftarrow 0$, $\mathtt{pred}[1] \leftarrow \mathtt{None}$.
Let queue be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while queue *is not empty* **do**
    Remove front tuple (v_i, v_j) from queue.
    if $\mathtt{L}[j] = \infty$ **then**
        Add (v_j, v_k) to queue for all $\{v_j, v_k\} \in E$, $k \neq i$.
        Set $\mathtt{L}[j] \leftarrow \mathtt{L}[i] + 1$, $\mathtt{pred}[j] = i$.
Return L and pred.

Breadth-first search: Implementation

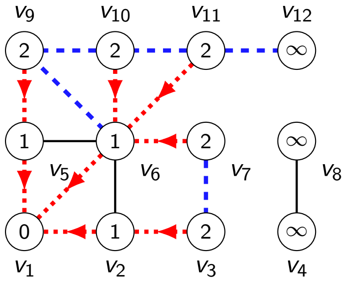


queue : $(9, 10), (9, 6), (10, 11), (10, 9),$
$(11, 10), (11, 12), (7, 3)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \ldots, v_n$.
Let $\mathtt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\mathtt{L}[1] \leftarrow 0$, $\mathtt{pred}[1] \leftarrow \mathtt{None}$.
Let `queue` be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while `queue` *is not empty* **do**
  Remove front tuple (v_i, v_j) from `queue`.
  if $\mathtt{L}[j] = \infty$ **then**
    Add (v_j, v_k) to `queue` for all $\{v_j, v_k\} \in E$, $k \neq i$.
    Set $\mathtt{L}[j] \leftarrow \mathtt{L}[i] + 1$, $\mathtt{pred}[j] = i$.
Return `L` and `pred`.



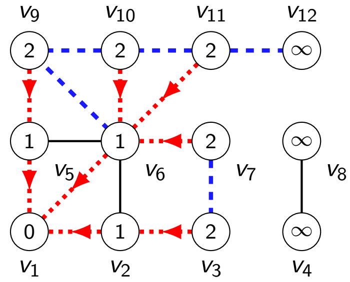
queue : $(9,10),(9,6),(10,11),(10,9),$
$(11,10),(11,12),(7,3),(3,7)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \ldots, v_n$.
Let `L`$[i] \leftarrow \infty$ for all $i \in [n]$.
Let `L`$[1] \leftarrow 0$, `pred`$[1] \leftarrow$ `None`.
Let `queue` be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while `queue` *is not empty* **do**
  Remove front tuple (v_i, v_j) from `queue`.
  if `L`$[j] = \infty$ **then**
    Add (v_j, v_k) to `queue` for all $\{v_j, v_k\} \in E$, $k \neq i$.
    Set `L`$[j] \leftarrow$ `L`$[i] + 1$, `pred`$[j] = i$.
Return `L` and `pred`.

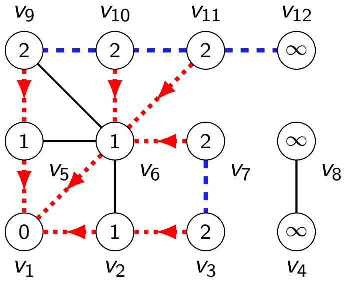
Breadth-first search: Implementation



queue : $(9,6),(10,11),(10,9),(11,10),$
$(11,12),(7,3),(3,7)$

Algorithm: BFS

```
Input  : Graph G = (V, E), vertex v ∈ V.
Output : d(v, y) for all y ∈ V and "a way of
         finding shortest paths".
Number the vertices of G as v = v_1, ..., v_n.
Let L[i] ← ∞ for all i ∈ [n].
Let L[1] ← 0, pred[1] ← None.
Let queue be a queue containing all tuples
  (v, v_j) with {v, v_j} ∈ E.
while queue is not empty do
    Remove front tuple (v_i, v_j) from queue.
    if L[j] = ∞ then
        Add (v_j, v_k) to queue for all
          {v_j, v_k} ∈ E, k ≠ i.
        Set L[j] ← L[i] + 1, pred[j] = i.
Return L and pred.
```



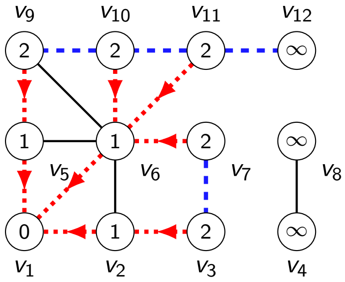
queue : $(10, 11), (10, 9), (11, 10), (11, 12),$
$(7, 3), (3, 7)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \ldots, v_n$.
Let $\texttt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\texttt{L}[1] \leftarrow 0$, $\texttt{pred}[1] \leftarrow$ `None`.
Let `queue` be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while `queue` *is not empty* **do**
  Remove front tuple (v_i, v_j) from `queue`.
  if $\texttt{L}[j] = \infty$ **then**
    Add (v_j, v_k) to `queue` for all $\{v_j, v_k\} \in E$, $k \neq i$.
    Set $\texttt{L}[j] \leftarrow \texttt{L}[i] + 1$, $\texttt{pred}[j] = i$.
Return `L` and `pred`.

Breadth-first search: Implementation



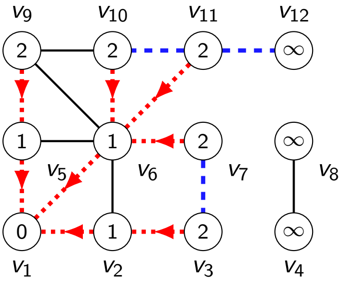
queue : (10, 9), (11, 10), (11, 12), (7, 3), (3, 7)

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \ldots, v_n$.
Let $\texttt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\texttt{L}[1] \leftarrow 0$, $\texttt{pred}[1] \leftarrow \texttt{None}$.
Let queue be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while queue *is not empty* **do**
  Remove front tuple (v_i, v_j) from queue.
  if $\texttt{L}[j] = \infty$ **then**
    Add (v_j, v_k) to queue for all $\{v_j, v_k\} \in E$, $k \neq i$.
    Set $\texttt{L}[j] \leftarrow \texttt{L}[i] + 1$, $\texttt{pred}[j] = i$.
Return L and pred.

Breadth-first search: Implementation

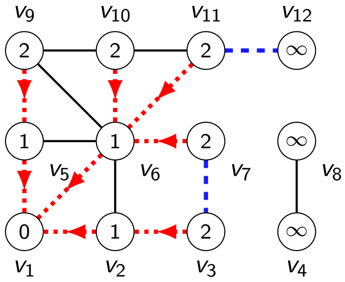


$\texttt{queue}: (11, 10), (11, 12), (7, 3), (3, 7)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \ldots, v_n$.
Let $\texttt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\texttt{L}[1] \leftarrow 0$, $\texttt{pred}[1] \leftarrow \texttt{None}$.
Let $\texttt{queue}$ be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while $\texttt{queue}$ *is not empty* **do**
  Remove front tuple (v_i, v_j) from $\texttt{queue}$.
  if $\texttt{L}[j] = \infty$ **then**
    Add (v_j, v_k) to $\texttt{queue}$ for all $\{v_j, v_k\} \in E$, $k \neq i$.
    Set $\texttt{L}[j] \leftarrow \texttt{L}[i] + 1$, $\texttt{pred}[j] = i$.
Return $\texttt{L}$ and $\texttt{pred}$.



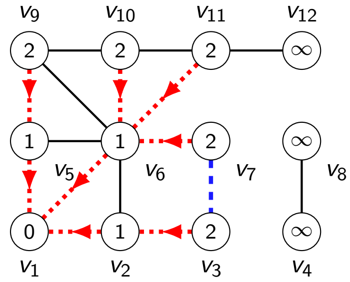
queue: $(11, 12), (7, 3), (3, 7)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \ldots, v_n$.
Let `L`$[i] \leftarrow \infty$ for all $i \in [n]$.
Let `L`$[1] \leftarrow 0$, `pred`$[1] \leftarrow$ `None`.
Let `queue` be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while `queue` *is not empty* **do**
  Remove front tuple (v_i, v_j) from `queue`.
  if `L`$[j] = \infty$ **then**
    Add (v_j, v_k) to `queue` for all $\{v_j, v_k\} \in E$, $k \neq i$.
    Set `L`$[j] \leftarrow$ `L`$[i] + 1$, `pred`$[j] = i$.

Return `L` and `pred`.

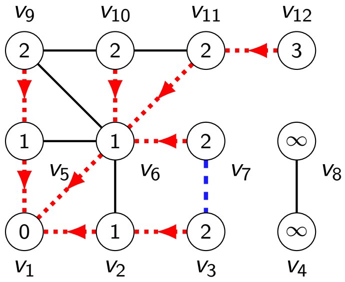


queue : $(7, 3), (3, 7)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \dots, v_n$.
Let $\texttt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\texttt{L}[1] \leftarrow 0$, $\texttt{pred}[1] \leftarrow \texttt{None}$.
Let queue be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while queue *is not empty* **do**
  Remove front tuple (v_i, v_j) from queue.
  if $\texttt{L}[j] = \infty$ **then**
    Add (v_j, v_k) to queue for all $\{v_j, v_k\} \in E$, $k \neq i$.
    Set $\texttt{L}[j] \leftarrow \texttt{L}[i] + 1$, $\texttt{pred}[j] = i$.
Return L and pred.

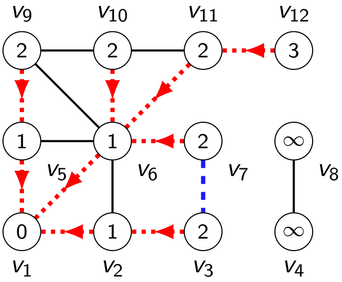


queue : $(7, 3), (3, 7)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \ldots, v_n$.
Let $\mathtt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\mathtt{L}[1] \leftarrow 0$, $\mathtt{pred}[1] \leftarrow \mathtt{None}$.
Let `queue` be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while `queue` *is not empty* **do**
    Remove front tuple (v_i, v_j) from `queue`.
    if $\mathtt{L}[j] = \infty$ **then**
        Add (v_j, v_k) to `queue` for all $\{v_j, v_k\} \in E$, $k \neq i$.
        Set $\mathtt{L}[j] \leftarrow \mathtt{L}[i] + 1$, $\mathtt{pred}[j] = i$.
Return L and pred.



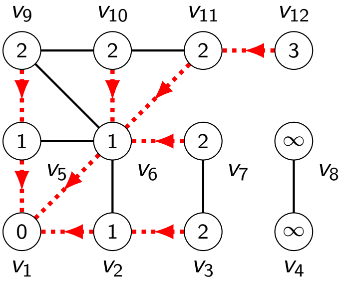
queue : $(3, 7)$

Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \dots, v_n$.
Let $\texttt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\texttt{L}[1] \leftarrow 0$, $\texttt{pred}[1] \leftarrow \texttt{None}$.
Let queue be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while queue *is not empty* **do**
  Remove front tuple (v_i, v_j) from queue.
  if $\texttt{L}[j] = \infty$ **then**
    Add (v_j, v_k) to queue for all $\{v_j, v_k\} \in E$, $k \neq i$.
    Set $\texttt{L}[j] \leftarrow \texttt{L}[i] + 1$, $\texttt{pred}[j] = i$.
Return L and pred.

Breadth-first search: Implementation

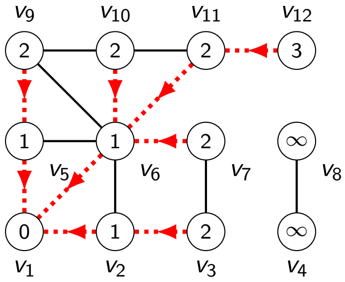


Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \ldots, v_n$.
Let $\mathtt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\mathtt{L}[1] \leftarrow 0$, $\mathtt{pred}[1] \leftarrow \mathtt{None}$.
Let $\mathtt{queue}$ be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while $\mathtt{queue}$ *is not empty* **do**
  Remove front tuple (v_i, v_j) from $\mathtt{queue}$.
  if $\mathtt{L}[j] = \infty$ **then**
    Add (v_j, v_k) to $\mathtt{queue}$ for all $\{v_j, v_k\} \in E$, $k \neq i$.
    Set $\mathtt{L}[j] \leftarrow \mathtt{L}[i] + 1$, $\mathtt{pred}[j] = i$.
Return $\mathtt{L}$ and $\mathtt{pred}$.

Breadth-first search: Implementation



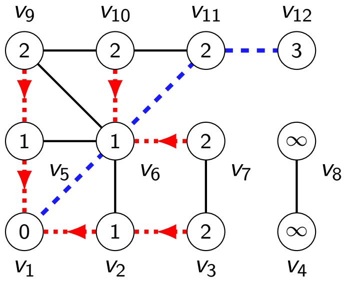
Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \dots, v_n$.
Let $\texttt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\texttt{L}[1] \leftarrow 0$, $\texttt{pred}[1] \leftarrow \texttt{None}$.
Let `queue` be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while `queue` *is not empty* **do**
  Remove front tuple (v_i, v_j) from `queue`.
  if $\texttt{L}[j] = \infty$ **then**
    Add (v_j, v_k) to `queue` for all $\{v_j, v_k\} \in E$, $k \neq i$.
    Set $\texttt{L}[j] \leftarrow \texttt{L}[i] + 1$, $\texttt{pred}[j] = i$.
Return `L` and `pred`.

In the output, $\texttt{L}[i] = d(v, v_i)$. By following edges back from v_i via `pred`, we can also quickly reconstruct a shortest path from v to v_i.

Breadth-first search: Implementation



Algorithm: BFS

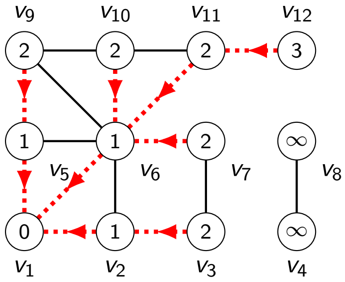
Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

```
Number the vertices of G as v = v_1, ..., v_n.
Let L[i] ← ∞ for all i ∈ [n].
Let L[1] ← 0, pred[1] ← None.
Let queue be a queue containing all tuples
  (v, v_j) with {v, v_j} ∈ E.
while queue is not empty do
    Remove front tuple (v_i, v_j) from queue.
    if L[j] = ∞ then
        Add (v_j, v_k) to queue for all
          {v_j, v_k} ∈ E, k ≠ i.
        Set L[j] ← L[i] + 1, pred[j] = i.
Return L and pred.
```

In the output, $L[i] = d(v, v_i)$. By following edges back from v_i via pred, we can also quickly reconstruct a shortest path from v to v_i.

E.g. $v_1 v_6 v_{11} v_{12}$ is a shortest path from v_1 to v_{12}.

Breadth-first search: Implementation

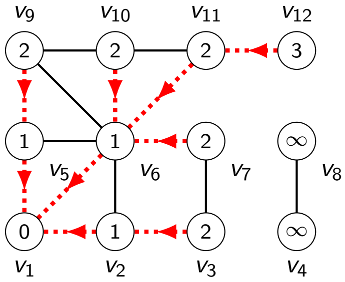


Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

Number the vertices of G as $v = v_1, \dots, v_n$.
Let $\mathtt{L}[i] \leftarrow \infty$ for all $i \in [n]$.
Let $\mathtt{L}[1] \leftarrow 0$, $\mathtt{pred}[1] \leftarrow \mathtt{None}$.
Let queue be a queue containing all tuples (v, v_j) with $\{v, v_j\} \in E$.
while queue *is not empty* **do**
    Remove front tuple (v_i, v_j) from queue.
    if $\mathtt{L}[j] = \infty$ **then**
        Add (v_j, v_k) to queue for all $\{v_j, v_k\} \in E$, $k \neq i$.
        Set $\mathtt{L}[j] \leftarrow \mathtt{L}[i] + 1$, $\mathtt{pred}[j] = i$.
Return L and pred.

Time analysis: If G is in adjacency list form, each edge is added to queue at most twice, incurring $O(1)$ overhead each time, so the running time is $O(|V| + |E|)$.



Algorithm: BFS

Input : Graph $G = (V, E)$, vertex $v \in V$.
Output : $d(v, y)$ for all $y \in V$ and "a way of finding shortest paths".

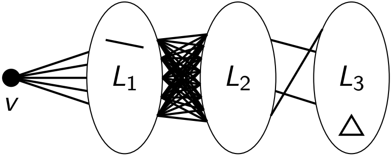
```
Number the vertices of G as v = v_1, ..., v_n.
Let L[i] ← ∞ for all i ∈ [n].
Let L[1] ← 0, pred[1] ← None.
Let queue be a queue containing all tuples
  (v, v_j) with {v, v_j} ∈ E.
while queue is not empty do
    Remove front tuple (v_i, v_j) from queue.
    if L[j] = ∞ then
        Add (v_j, v_k) to queue for all
          {v_j, v_k} ∈ E, k ≠ i.
        Set L[j] ← L[i] + 1, pred[j] = i.
Return L and pred.
```

Important: There is a significant **space** inefficiency in this version of breadth-first search! See example sheet.

BFS trees

Definition: A **BFS tree** T of G is a rooted tree (call its root x) with:

1. $V(T)$ is the vertex set of a component of G;
2. The i'th layer of T is $\{x\colon d_G(x,v) = i\}$;
3. If $\{x,y\} \in E(G)$, then $|d_G(v,x) - d_G(v,y)| \leq 1$, i.e. x and y must be in the same or adjacent layers of T.

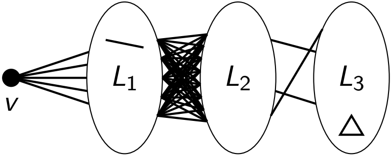


Theorem: The tree of edges from `pred` is always a BFS tree.

BFS trees

Definition: A **BFS tree** T of G is a rooted tree (call its root x) with:

1. $V(T)$ is the vertex set of a component of G;
2. The i'th layer of T is $\{x\colon d_G(x,v) = i\}$;
3. If $\{x,y\} \in E(G)$, then $|d_G(v,x) - d_G(v,y)| \le 1$, i.e. x and y must be in the same or adjacent layers of T.



Theorem: The tree of edges from `pred` is always a BFS tree.

Proof: We already proved (1) and (2), so suppose $\{x,y\} \in E(G)$.

If P is a shortest path from v to x, then Pxy is a path from v to y, so $d(v,y) \le d(v,x) + 1$. Likewise $d(v,x) \le d(v,y) + 1$. ✓