Directed graphs

A directed graph consists of a collection of vertices (also called nodes) together with a collection of edges.

An edge is an ordered pair of vertices, which we can represent by an arrow from one vertex to another.
We have seen such graphs before.

Evolution trees and expression trees were both directed graphs of a special type.

An edge represented a parent-child relationship.

Graphs are a general data structure that can model many situations.

Computations on graphs form an important part of the computer science toolkit.

Graph terminology

Given an edge \((v, w)\), we say that \(w\) is an out-neighbour of \(v\), and \(v\) is an in-neighbour of \(w\).

A sequence of vertices \(v_1, v_2, \ldots, v_k\) is a path or route of length \(k - 1\) if \((v_1, v_2), (v_2, v_3), \ldots, (v_{k-1}, v_k)\) are all edges.

If \(v_1 = v_k\), this is called a cycle.

Directed graphs without cycles are called DAGs (directed acyclic graphs).

Representing graphs

We can represent a node by a symbol (its name), and associate with each node a list of its out-neighbours.

This is called the adjacency list representation.

More specifically, a graph is a list of pairs, each pair consisting of a symbol (the node’s name) and a list of symbols (the names of the node’s out-neighbours).

This is very similar to a parent node with a list of children.
Our example as data

'((A (C D E))
 (B (E J))
 (C ())
 (D (F J))
 (E (K))
 (F (K H))
 (H ())
 (J (H))
 (K ()))

Data definitions

To make our contracts more descriptive, we will define a Node and a Graph as follows:

;; A Node is a Sym

;; A Graph is a (listof (list Node (listof Node)))

The template for graphs

;; graph-template: Graph → Any
(define (graph-template G)
 (cond
  [(empty? G) . . .]
  [(cons? G)
   (. . . (first (first G)) . . . ; first node in graph list
    (listof-node-template (second (first G))) . . . ; list of adjacent nodes
    (graph-template (rest G)) . . .)])
Finding routes

A path in a graph can be represented by the list of nodes on the path.

We wish to design a function `find-route` that consumes a graph plus origin and destination nodes, and produces a path from the origin to the destination, or `false` if no such path exists.

First we create an auxiliary function `neighbours` that consumes a node and a graph and produces the list of out-neighbours of the node.

```
;; (neighbours v G) produces list of neighbours of v in G
;; neighbours: Node Graph → (listof Node)
;; requires: v is a node in G
(define (neighbours v G)
  (cond [(symbol=? v (first (first G))) (second (first G))]
        [else (neighbours v (rest G))]))
```

Neighbours in our example

(neighbours 'A G) ⇒ (list 'C 'D 'E)
(neighbours 'H G) ⇒ empty
**Cases for find-route**

Structural recursion does not work for find-route; we must use generative recursion.

If the origin equals the destination, the path consists of just this node.

Otherwise, if there is a path, the second node on that path must be an out-neighbour of the origin node.

Each out-neighbour defines a subproblem (finding a route from it to the destination).

In our example, any route from A to H must pass through C, D, or E.

If we knew a route from C to H, or from D to H, or from E to H, we could create one from A to H.

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**Backtracking algorithms**

Backtracking algorithms try to find a route from an origin to a destination.

If the initial attempt does not work, such an algorithm “backtracks” and tries another choice.

Eventually, either a route is found, or all possibilities are exhausted, meaning there is no route.
In our example, we can see the “backtracking” since the search for a route from A to H can be seen as moving forward in the graph looking for H.

If this search fails (for example, at C), then the algorithm “backs up” to the previous vertex (A) and tries the next neighbour (D).

If we find a path from D to H, we can just add A to the beginning of this path.

We need to apply find-route on each of the out-neighbours of a given node.

All those out-neighbours are collected into a list associated with that node.

This suggests writing find-route/list which does this for the entire list of out-neighbours.

The function find-route/list will apply find-route to each of the nodes on that list until it finds a route to the destination.

This is the same recursive pattern that we saw in the processing of expression trees (and descendant family trees, in HtDP).

For expression trees, we had two mutually recursive functions, eval and apply.

Here, we have two mutually recursive functions, find-route and find-route/list.
;; (find-route orig dest G) finds route from orig to dest in G if it exists
;; find-route: Node Node Graph → (anyof (listof Node) false)
(define (find-route orig dest G)
  (cond [((symbol=? orig dest) (list orig))
      [else (local [(define nbrs (neighbours orig G))
                    (define route (find-route/list nbrs dest G))]
               (cond [(false? route) route]
                      [else (cons orig route)]))))))

;; (find-route/list los dest G) produces route from an element of los to dest in G, if one exists
;; find-route/list: (listof Node) Node Graph → (anyof (listof Node) false)
(define (find-route/list los dest G)
  (cond [(empty? los) false]
        [else (local [(define route (find-route (first los) dest G))]
                   (cond [(false? route) (find-route/list (rest los) dest G)]
                          [else route]))])))

If we wish to trace find-route, trying to do a linear trace would be very long, both in terms of steps and the size of each step. Our traces also are listed as a linear sequence of steps, but but the computation in find-route is better visualized as a tree.

We will use an alternate visualization of the potential computation (which could be shortened if a route is found).

The next slide contains the trace tree. We have omitted the arguments dest and G which never change.
Backtracking in implicit graphs

The only places where real computation is done on the graph is in comparing the origin to the destination and in the neighbours function.

Backtracking can be used without having the entire graph available.

Example: nodes represent configurations of a board game (e.g. peg solitaire), edges represent legal moves.

The graph is acyclic if no configuration can occur twice in a game.

In another example, nodes could represent partial solutions of some problem (e.g. a sudoku puzzle, or the puzzle of putting eight mutually nonattacking queens on a chessboard).

Edges represent ways in which one additional element can be added to a solution.

The graph is naturally acyclic, since a new element is added with every edge.
The **find-route** functions for implicit backtracking look very similar to those we have developed.

The neighbours function must now generate the set of neighbours of a node based on some description of that node (e.g. the placement of pieces in a game).

This allows backtracking in situations where it would be inefficient to generate and store the entire graph as data.

Backtracking forms the basis of many artificial intelligence programs, though they generally add heuristics to determine which neighbour to explore first, or which ones to skip because they appear unpromising.

### Termination of **find-route** (no cycles)

In a directed acyclic graph, any route with a given origin will recurse on its (finite number) of neighbours by way of **find-route/list**. The origin will never appear in this call or any subsequent calls to **find-route**: if it did, we would have a cycle in our DAG.

Thus, the origin will never be explored in any later call, and thus the subproblem is smaller. Eventually, we will reach a subproblem of size 0 (when all reachable nodes are treated as the origin).

Thus **find-route** always terminates for directed acyclic graphs.
Non-termination of **find-route** (cycles)

It is possible that **find-route** may not terminate if there is a cycle in the graph.

Consider the graph `(((A (B)) (B (C)) (C (A)) (D ()))).` What if we try to find a route from A to D?

![Graph diagram]

```
(find-route 'A)
(find-route/list '(B))
  (find-route 'B)
  (find-route/list '(C))
    (find-route 'C)
    (find-route/list '(A))
      (find-route 'A)
      (find-route/list '(B))
...
```

**Improving find-route**

We can use accumulative recursion to solve the problem of **find-route** possibly not terminating if there are cycles in the graph.

To make backtracking work in the presence of cycles, we need a way of remembering what nodes have been visited (along a given path).

Our accumulator will be a list of visited nodes.

We must avoid visiting a node twice.

The simplest way to do this is to add a check in **find-route/list**.
The code for `find-route/list` does not add anything to the accumulator (though it uses the accumulator).

Adding to the accumulator is done in `find-route/acc` which applies `find-route/list` to the list of neighbours of some origin node.

That origin node must be added to the accumulator passed as an argument to `find-route/list`. 

---

The code for `find-route/acc`:

```scheme
;; Node Node Graph (listof Node) → (anyof (listof Node) false)
(define (find-route/acc orig dest G visited)
  (cond [(symbol=? orig dest) (list orig)]
       [else (local [[(define nbru (neighbours orig G))]
                     [(define route (find-route/list nbru dest G (cons orig visited)))]
                     [(false? route) route]
                     [else (cons orig route)])]]))
```

---

The code for `find-route/list` does not add anything to the accumulator (though it uses the accumulator).
Revisiting our example

Note that the value of the accumulator in `find-route/list` is always the reverse of the path from A to the current origin (first argument).

This example has no cycles, so the trace only convinces us that we haven’t broken the function on acyclic graphs, and shows us how the accumulator is working.

But it also works on graphs with cycles.

The accumulator ensures that the depth of recursion is no greater than the number of nodes in the graph, so `find-route` terminates.
In practice, we would write a wrapper function for users which would avoid their having to specify the initial value of the accumulator, as we have with the other examples in this module. Backtracking now works on graphs with cycles, but it can be inefficient, even if the graph has no cycles. If there is no path from the origin to the destination, then find-route will explore every path from the origin, and there could be an exponential number of them.

If there are $d$ diamonds, then there are $3d + 2$ nodes in the graph, but $2^d$ paths from A to Y, all of which will be explored.
Making **find-route/acc** efficient

Applying **find-route/acc** to origin A results in **find-route/list** being applied to '(B1 B2), and then **find-route/acc** being applied to origin B1.

There is no route from B1 to Z, so this will produce **false**, but in the process, it will visit all the other nodes of the graph except B2 and Z. **find-route/list** will then apply **find-route/acc** to B2, which will visit all the same nodes.

When **find-route/list** is applied to the list of nodes los, it first applies **find-route/acc** to (first los) and then, if that fails, it applies itself to (rest los).

To avoid revisiting nodes, the failed computation should pass the list of nodes it has seen on to the next computation.

It will do this by returning the list of visited nodes instead of **false** as the sentinel value. However, we must be able to distinguish this list from a successfully found route (also a list of nodes).

Remembering what the list of nodes represents

We will make a new type that will store both the list of nodes (either those nodes which have been visited, or the nodes along the successful path) as well as a boolean value indicating what the list of nodes represents.

```
(define-struct route (valid-path? nodes))
;; a Route is a (make-route Bool (listof Node))
```
(find-route/list los dest G visited)

(define (find-route/list los dest G visited)
  (cond [(empty? los) (make-route false visited)]
        [(member? (first los) visited) (find-route/list (rest los) dest G visited)]
        [else (local [(define route (find-route/acc (first los) dest G visited))
                      (cond [[(not (route-valid-path? route))
                               (find-route/list (rest los) dest G
                                (route-nodes route))]  
                              [else route]]))])])

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(define (find-route/acc orig dest G visited)
  (cond [(symbol=? orig dest) (make-route true (list orig))]
        [else (local [(define nbrs (neighbours orig G))
                      (define route (find-route/list nbrs dest G
                                    (cons orig visited)))
                      (cond [[(not (route-valid-path? route)) route]
                              [else (make-route true (cons orig route))])])])

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(define (find-route orig dest G)
  (local [(define route (find-route/acc orig dest G empty))]
         (cond [[(route-valid-path? route) (route-nodes route)]
                [else false]]))

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With these changes, find-route runs much faster on the diamond graph.

How efficient is our final version of find-route?

Each node is added to the visited accumulator at most once, and once it has been added, it is not visited again.

Thus find-route/acc is applied at most \( n \) times, where \( n \) is the number of nodes in the graph.

One application of find-route/acc (not counting recursions) takes time roughly proportional to \( n \) (mostly in neighbours).

The total work done by find-route/acc is roughly proportional to \( n^2 \).

One application of find-route/list takes time roughly proportional to \( n \) (mostly in member?).

find-route/list is applied at most once for every node in a neighbour list, that is, at most \( m \) times, where \( m \) is the number of edges in the graph.

The total cost is roughly proportional to \( n(n + m) \).
We will see how to make \texttt{find-route} even more efficient in later courses, and see how to formalize our analyses.

Knowledge of efficient algorithms, and the data structures that they utilize, is an essential part of being able to deal with large amounts of real-world data.

These topics are studied in CS 240 and CS 341 (for majors) and CS 234 (for non-majors).

\section*{Goals of this module}

You should understand directed graphs and their representation in Racket.

You should be able to write functions which consume graphs and compute desired values.

You should understand and be able to implement backtracking on explicit and implicit graphs.

You should understand the performance differences in the various versions of \texttt{find-route} and be able to write more efficient functions using appropriate recursive techniques.