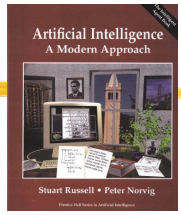
Resources



- Search Techniques:
  - Stuart Russell and Peter Norvig, "Artificial Intelligence: A Modern Approach", Prentice Hall, 2002 (£40 used, library)
  - Judea Pearl, "Heuristics: Intelligent Search Strategies for Computer Problem Solving", Addison Wesley, 1984 (library)
  - Nils Nilsson, "Problem Solving Methods in Artificial Intelligence", McGraw-Hill, 1971 (library)
- Java sources to augment assessment on course webpage

2nd assessment

- Navigation puzzle around square obstacles:
  - Plan a route around 16 obstacles
  - Individualised set of obstacles
  - Individualised start and destination locations
  - Marks for **correct answers** on fixed planning problems
  - Marks for correct code
  - Marks for short (**tight**) code
- Deadline and weighting:
  - Tuesday of week 20 (3rd March 2020)
  - Worth 25% of co528

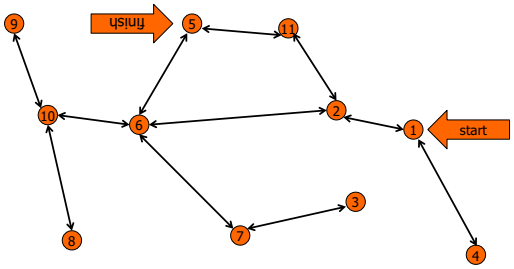
Part I

Route finding and iterative deepening

Historical perspective on "Look Ma, no hands" era

- [Newell and Ernest, *IFIP Congress*, 1965] introduced the phrase "heuristic search"
- [Doran and Michie, *Proceedings of the Royal Society of London*, 294, 1966] developed heuristics for the 8-puzzle and the 15-puzzle
- [Hart, Nilsson and Raphael, *Systems Science and Cybernetics*, SSC-4, 1968] developed A* search; [Erratum in *SIGART*, 1972] (see survey by Nilsson)

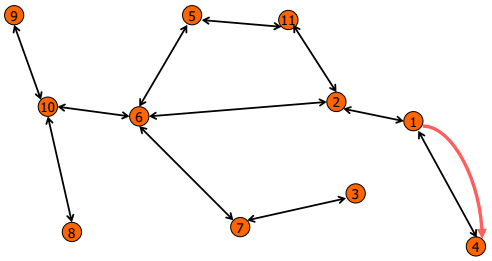
Iterative deepening example



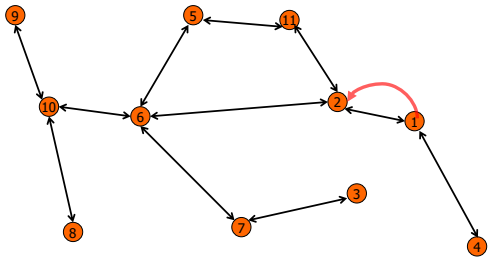
Iterative deepening algorithm (with deja vu)

- Phase 1:
  - Enumerate all paths of length 1
- Phase 2:
  - Enumerate all paths of length 2
- Phase 3:
  - …

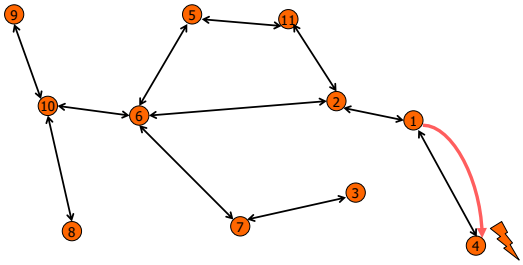
Phase 1 start



Phase 1 finish

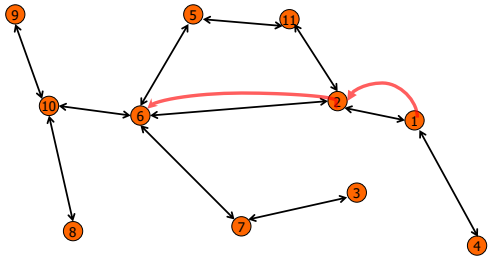


Phase 2 start

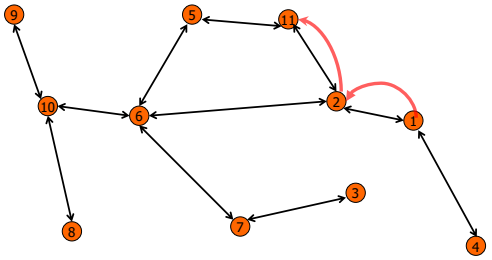


But cannot extend path through 4

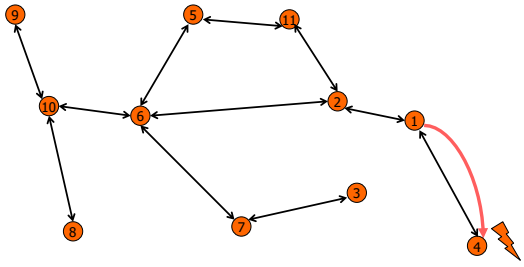
Phase 2 continued



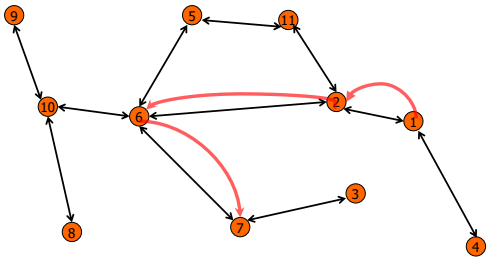
Phase 2 finish



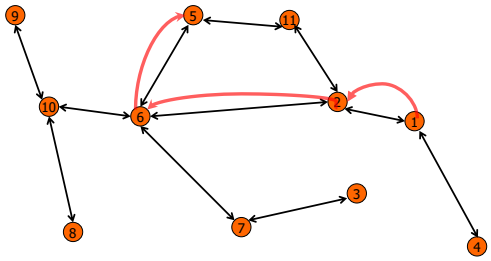
Phase 3 start



Phase 3 continued



Phase 3 finish (reached destination)



Is redoing work OK?

- Phase 2 redoes all the work of Phase 1
- Phase 3 redoes all the work of Phase 2
- Phase k+1 redoes all the work of Phase k
- Suppose we explore twice as many extra paths at each phase:

Phase	Paths	Total Paths		Ratio Paths/Total Paths
1	2	2	= 2	2/2 = 1
2	4	2 + 4	= 6	4/6 = 2/3
3	8	2 + 4 + 8	= 14	8/14 = 4/7
4	16	2 + 4 + 8 + 16	= 30	16/30 = 8/15

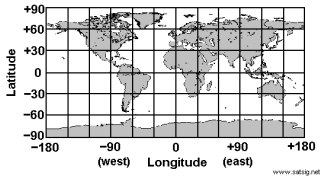
Is redoing work OK?

- **Yes**, because iterative deepening is:

Routefinder for Kent

Longitude (x) and latitude (y) coordinates (towns.xls)

ashford	ash	51.1534	0.8746
barham	bar	51.2081	1.1586
canterbury	cant	51.2783	1.0776
chartham	chart	51.255	1.0205
cranbrook	cran	51.0968	0.5354
deal	deal	51.2251	1.3992
dungeness	dung	50.9164	0.9742
dover	dov	51.1295	1.3089
faversham	fav	51.3168	0.89
folkestone	folk	51.0815	1.166
gillingham	gill	51.3839	0.5609
gravesend	graves	51.4419	0.3707
harrietsham	harr	51.244	0.6673
hastings	hast	50.8539	0.5748
herne_bay	hb	51.3735	1.1257
hythe	hy	51.0726	1.0805
maidstone	maid	51.2751	0.5205
margate	mar	51.3893	1.3874
new_romney	nr	50.9859	0.9397
ramsgate	rams	51.3363	1.4211
rye	rye	50.9498	0.7373
sandwich	sand	51.2771	1.337
sheerness	sheer	51.4421	0.756
sittingbourne	sit	51.3378	0.7321
sturry	st	51.3036	1.1211
tenterden	tent	51.0694	0.6891
whitstable	whit	51.3621	1.0223



Adjacency list

```
{ash➔[chart, fav, folk, harr, hy, nr, rye, tent],
bar➔[cant, dov, folk], cant➔[bar, chart, fav, sand,
st, whit], chart➔[ash, cant, harr], cran➔[hast,
maid], deal➔[dov, sand], dov➔[bar, deal, folk,
sand], dung➔[], fav➔[ash, cant, whit], folk➔[ash,
bar, dov, hy], gill➔[graves, sit], graves➔[gill,
maid], harr➔[ash, chart, maid], hast➔[cran, rye,
tent], hb➔[mar, st, whit], hy➔[ash, folk, nr],
maid➔[cran, graves, harr, sit, tent], mar➔[hb,
rams, st], nr➔[ash, hy, rye], rams➔[mar, sand, st],
rye➔[ash, hast, nr, tent], sand➔[cant, deal, dov,
rams], sheer➔[sit], sit➔[gill, maid, sheer],
st➔[cant, hb, mar, rams], tent➔[ash, hast, maid,
rye], whit➔[cant, fav, hb]}
```

Realising iterative deepening

- Enumerate all paths of length =< 1
- Enumerate all paths of length =< 2
- Enumerate all paths of length =< 3
- ...
- Use depth-first (limited) search

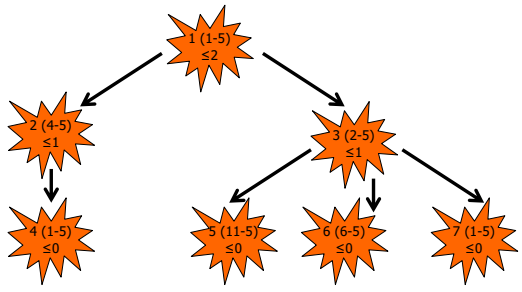
Depth-first (limited) search

```
private LinkedList<Town> depthFirst(Town start, Town dest, int depth)
{       if (start.equals(dest))
        {
                LinkedList<Town> route = new LinkedList<Town>();
                route.add(dest); // construct singleton route
                return route;
        }
        else if (depth == 0) return null;
        else
        {
                LinkedList<Town> nextTowns = graph.get(start);
                for (Town next:nextTowns)     // search top-down
                {       LinkedList<Town> route = depthFirst(next, dest, depth - 1);
                        if (route != null)
                        {
                                route.addFirst(start);
                                return route;
                        }
                }
                return null;
        }
}
```

Does it terminate?

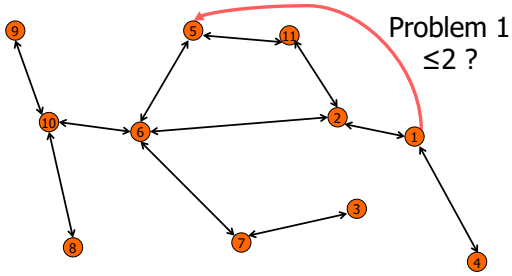
- Check the arguments
- Check the size of the arguments
- Just need one argument to always get smaller on each recursive call

Problem decomposition for depth-first (limited) search

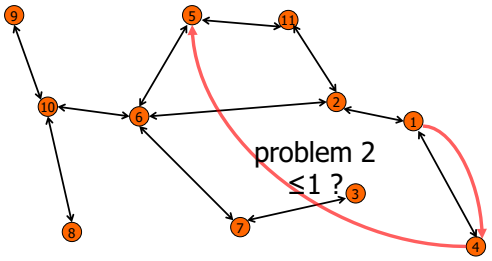


Problems are considered top-down left-to-right

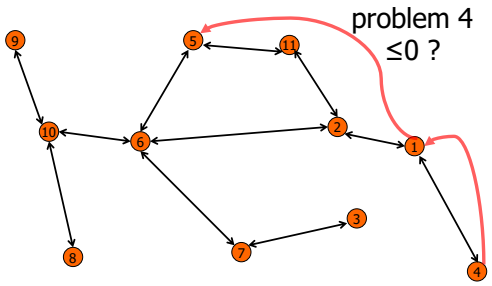
Depth-first (limited to 2)



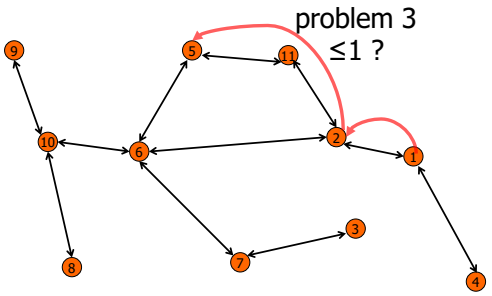
Reducing problem 1 (1-5) to problem 2 (4-5)



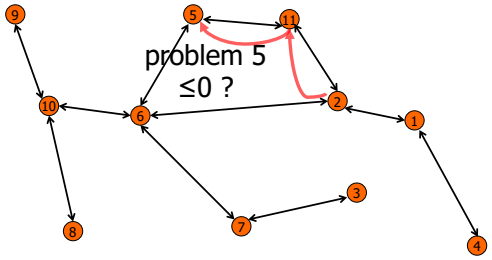
Reducing problem 2 (4-5) to problem 4 (1-5)



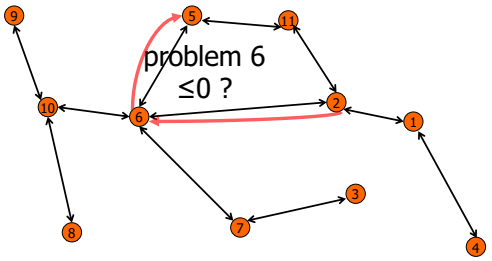
Reducing problem 1 (1-5) to problem 3 (2-5)



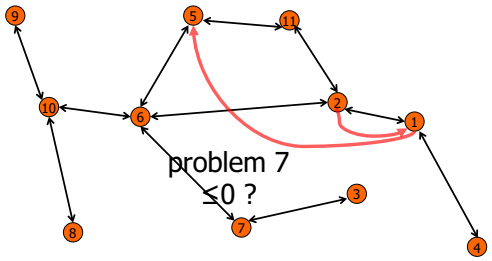
Reducing problem 3 (2-5) to problem 5 (11-5)



Reducing problem 3 (2-5) to problem 6 (6-5)



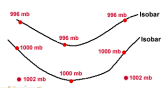
Reducing problem 3 (2-5) to problem 7 (1-5)

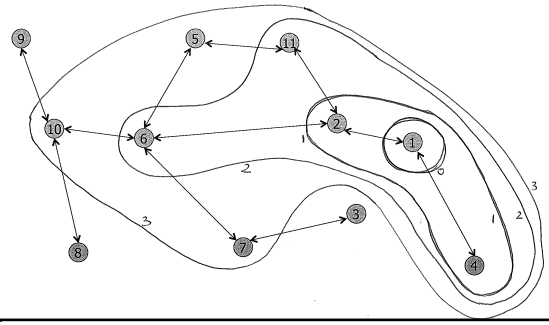


Iterative deepening

```
private LinkedList<Town> iterativeDeepening(Town start, Town dest)
{
      for (int depth = 1; true; depth++)        // doubtful termination
      {
          LinkedList<Town> route = depthFirst(start, dest, depth);
          if (route != null) return route;          // fast exit
      }
}
```

Contour map for Iterative deepening





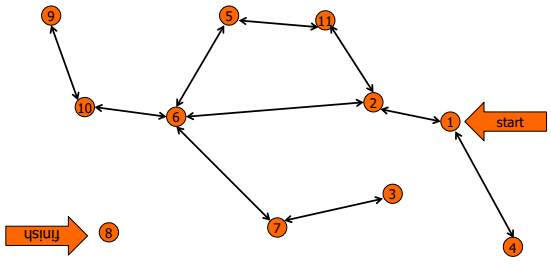
Completeness/incompleteness

- A search algorithm is said to be ***complete*** if, given enough resource, it will either:
  - find a route between two points
  - find that no route exists between two points
- A search algorithm that is not complete is said to be ***incomplete***
- Note that an incomplete algorithm may not terminate for some problems!

Iterative deepening versus depth-first (limited) search

- Iterative deepening is incomplete since:
  - if no route exists, then deepening will continue *ad infinitum*
- Whether depth-limited search is complete depends on the depth parameter:
  - for completeness set the depth to be the number of vertices in the network (or one less)

Showing incompleteness of iterative deepening



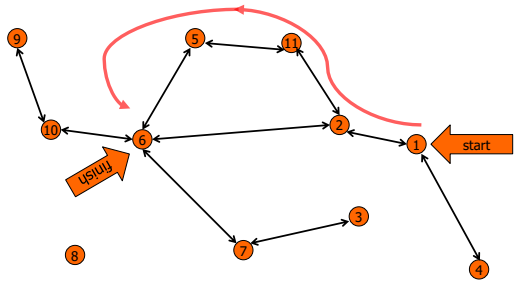
Optimality/sub-optimality

- A search algorithm is said to be ***optimal*** if, given enough resource, it will:
  - always find a shortest route between two points if a route exists between those points
- A search algorithm that is not optimal is said to be ***sub-optimal***
- Note that there may not be a unique shortest route between two configurations

Iterative deepening versus depth-first (limited) search

- Suppose the optimality criteria is route length
- Iterative deepening is optimal since:
  - it will only consider a route of length k+1 when all routes of length k have already been considered
- Depth-first limited search is sub-optimal because:
  - the only guarantee is that the length of the route will not exceed the limit

Showing incompleteness of iterative deepening



What is a Town?

- Problem specific class for state/configuration
- LinkedList<Town> route hence route is a list (sequence) of Town objects
- List is created once destination reached (bottom-up strategy)
- List is not extended (top-down strategy)
- Top-down can support deja vu checking

Depth-limited search without repetition (1 of 2)

```
private LinkedList<Town> depthFirstDevaVu(LinkedList<Town> route,
                                          Town dest, int depth)
{
    if (depth == 0) return null;

    Town last = route.getLast();

    if (last.equals(dest)) return route;
    else
    {
            LinkedList<Town> nextTowns = graph.get(last);
            for (Town next:nextTowns)
                ....

    }
}
```

Depth-limited search without repetition (2 of 2)

```
for (Town next:nextTowns)
{
    if (!route.contains(next))
    {
        LinkedList<Town> nextRoute = (LinkedList<Town>) route.clone();
        nextRoute.add(next);
        LinkedList<Town> wholeRoute =
            depthFirstDevaVu(nextRoute, dest, depth - 1);
        if (wholeRoute != null) return wholeRoute;
    }
}
```

Completeness/incompleteness

- A search algorithm is said to be ***complete*** if, given enough resource, it will either:
  - find a route between two points
  - find that no route exists between two points
- A search algorithm that is not complete is said to be ***incomplete***
- Note that an incomplete algorithm may not even terminate for some configurations!

Iterative deepening versus depth-limited search

- Iterative deepening is incomplete since:
  - if no route exists, then deepening will continue *ad infinitum*
- Depth-limited search is complete iff the limit is greater or equal to the length of shortest route between any two points:
  - if no route exists, then search will always detect failure (case 2)
  - if a route exists, then a shortest route exists, thus a route exists who length is smaller or equal to the limit, in which case such a route will be found (case 1)

Recover incompleteness with depth-limited search?

- Recall that depth-limited search is complete if the depth limit exceeds the length of the shortest route between any two points
- Any shortest path cannot contain two points configurations twice, otherwise the path can be shortened:
  - $[c_1, c_2, c_3, c_4, c_3, c_5] \rightarrow [c_1, c_2, c_3, c_5]$
- Thus the length of a shortest path cannot exceed the total number of ***different*** configurations
- Number of configurations is an upper bound on the length of any shortest path

Optimality/sub-optimality

- A search algorithm is said to be ***optimal*** if, given enough resource, it will:
  - always find a shortest route between two points if a route exists between those points
- A search algorithm that is not optimal is said to be ***sub-optimal***
- Note that there may not be a unique shortest route between two configurations

Iterative deepening versus depth-limited search (reprise)

- Suppose the optimality criteria is route length
- Iterative deepening is optimal since:
  - it will only consider a route of length k+1 when all routes of length k have already been considered
- Depth-limited search is sub-optimal because:
  - the only guarantee is that the length of the route will not exceed the limit