1

SHORTEST PATHS

Lecture 19
CS2110 – Spring 2015

Readings? Chapter 28

2

Do not write 2n = O(n) !!!!!!

3

Please tell your AEW facilitator NOT to write:

(1) 2n = O(n)

Instead, write: 2n is O(n)

Formula (1) is a misuse of mathematical notation, and it can can lead to misconceptions and errors, as shown on the next slide.

Instead of "Jack is tall" do you write "Jack = tall"? Of course not!

Do not write 2n = O(n) !!!!!!

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We know that 2n is O(n) and 3n is O(n)

Write these as 2n = O(n) and 3n = O(n)

Then, we have:

2n
= <above>
O(n)
= <above>
3n

So, using symmetry and transitivity of =, we have proved that

2n = 3n !!!!

Shortest Paths in Graphs

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Problem of finding shortest (min-cost) path in a graph occurs often

- Find shortest route between Ithaca and West Lafayette, IN
- Result depends on notion of cost
  - Least mileage… or least time… or cheapest
  - Perhaps, expends the least power in the butterfly while flying fastest
  - Many "costs" can be represented as edge weights

Every time you use googlemaps to find directions you are using a shortest-path algorithm

From Sid's to David's

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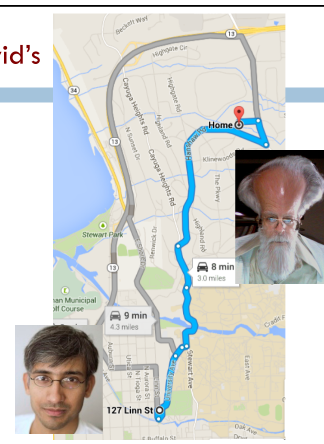
Use googlemaps to find a route from Sid's to David's house.

Gives three routes, depending on what is to be minimized.

Miles?
Driving time?
Use of big highways?
Scenic routes?



Shortest path?

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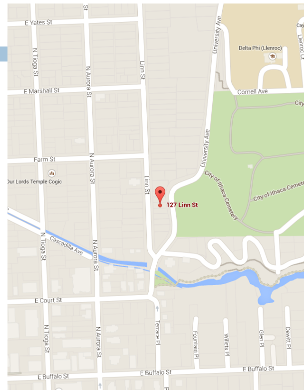
Each intersection is a node of the graph, and each road between two intersections has a weight

distance?
time to traverse?
…



Shortest path?

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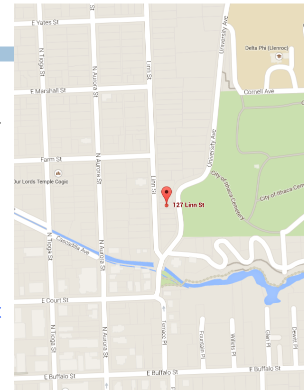
Fan out from the start node (kind of breadth-first search)

Settled set: Those whose shortest distance is known.

Frontier set: Those seen at least once but shortest distance not yet known



Shortest path?

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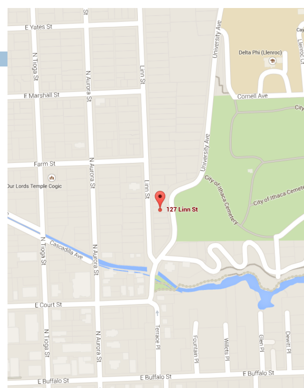
Fan out from the start node (kind of breadth-first search). Start:

Settled set:

Frontier set:

Choose the one in Frontier set with shortest distance from start



Shortest path?

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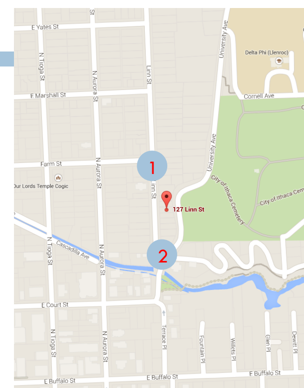
Fan out from start node. Recording shortest distance from start seen so far

Settled set:

Frontier set:

Now choose one in Frontier set with shortest distance from start



Shortest path?

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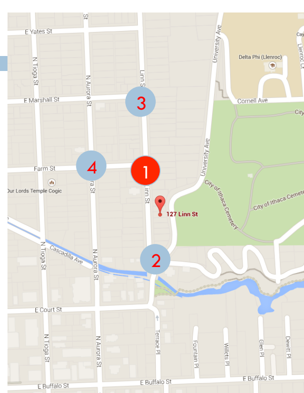
Fan out from start, recording shortest distance seen so far

Settled set:

Frontier set:

Now choose the one in Frontier set with shortest distance from start



Shortest path?

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Fan out from start, recording shortest distance seen so far

Settled set:

Frontier set:

Now choose the one in Frontier set with shortest distance

Shortest path?

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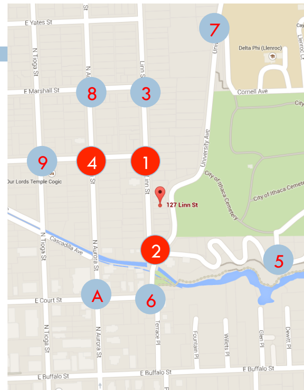
Fan out from start, recording shortest distance seen so far

Settled set: 1 2 4

Frontier set: 3 5 6 7 8 9 A

Now choose the one in Frontier set with shortest distance



Shortest path?

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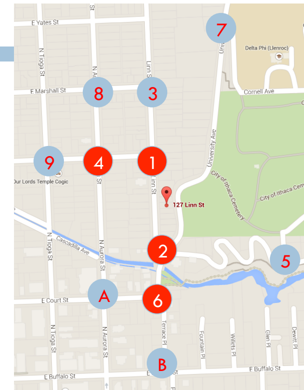
Fan out from start, recording shortest distance seen so far

Settled set: 1 2 4 6

Frontier set: 3 5 7 8 9 A B



Dijkstra's shortest-path algorithm

Edsger Dijkstra, in an interview in 2010 (*CACM*):

… the algorithm for the shortest path, which I designed in about 20 minutes. One morning I was shopping in Amsterdam with my young fiance, and tired, we sat down on the cafe terrace to drink a cup of coffee, and I was just thinking about whether I could do this, and I then designed the algorithm for the shortest path. As I said, it was a 20-minute invention. [Took place in 1956]

Dijkstra, E.W. A note on two problems in Connexion with graphs. *Numerische Mathematik* 1, 269–271 (1959).

Visit http://www.dijkstrascry.com for all sorts of information on Dijkstra and his contributions. As a historical record, this is a gold mine.

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Dijkstra's shortest-path algorithm

Dijsktra describes the algorithm in English:

- When he designed it in 1956 (he was 26 years old), most people were programming in assembly language!
- Only *one* high-level language: Fortran, developed by John Backus at IBM and not quite finished.

No theory of order-of-execution time —topic yet to be developed. In paper, Dijkstra says, "my solution is preferred to another one … "the amount of work to be done seems considerably less."

Dijkstra, E.W. A note on two problems in Connexion with graphs. *Numerische Mathematik* 1, 269–271 (1959).

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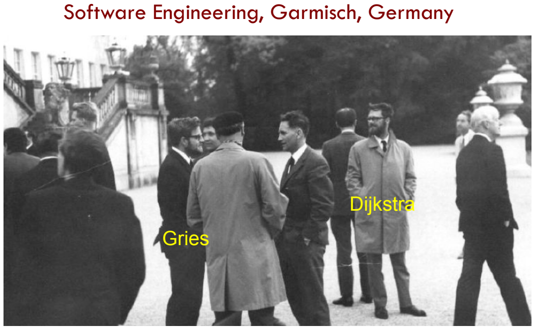
1968 NATO Conference on Software Engineering, Garmisch, Germany



Term "software engineering" coined for this conference

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1968 NATO Conference on Software Engineering

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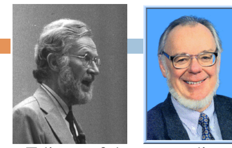
- In Garmisch, Germany
- Academicians and industry people attended
- For first time, people admitted they did not know what they were doing when developing/testing software. Concepts, methodologies, tools were inadequate, missing
- The term *software engineering* was born at this conference.
- The NATO Software Engineering Conferences:
  http://homepages.cs.ncl.ac.uk/brian.randell/NATO/index.html
  Get a good sense of the times by reading these reports!

1968 NATO Conference on Software Engineering, Garmisch, Germany

1968/69 NATO Conferences on Software Engineering

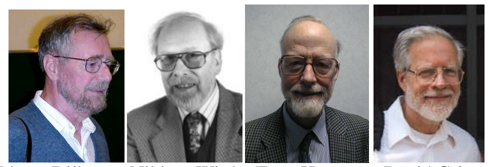


Editors of the proceedings

Beards

The reason why some people grow
aggressive tufts of facial hair
Is that they do not like to show
the chin that isn't there.

a grook by Piet Hein



Edsger Dijkstra Niklaus Wirth Tony Hoare David Gries

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Dijkstra' s shortest path algorithm

The n (> 0) nodes of a graph numbered 0..n-1.

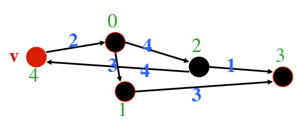
Each edge has a positive weight.

weight(v1, v2) is the weight of the edge from node v1 to v2.

Some node v be selected as the *start* node.

Calculate length of shortest path from v to each node.

Use an array L[0..n-1]: for **each** node w, store in L[w] the length of the shortest path from v to w.



L[0] = 2
L[1] = 5
L[2] = 6
L[3] = 7
L[4] = 0

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Dijkstra' s shortest path algorithm

Develop algorithm, not just present it.

Need to show you the state of affairs —the relation among all variables— just before each node i is given its final value L[i].

This relation among the variables is an *invariant*, because it is always true.

Because each node i (except the first) is given its final value L[i] during an iteration of a loop, the *invariant* is called a *loop invariant*.

L[0] = 2
L[1] = 5
L[2] = 6
L[3] = 7
L[4] = 0

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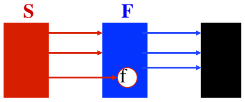
The loop invariant

Settled S **Frontier F** **Far off**

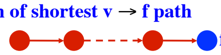


(edges leaving the black set and edges from the blue to the red set are not shown)

1. For a Settled node s, L[s] is length of shortest v → s path.

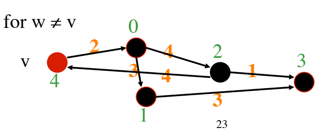
2. All edges leaving S go to F.

3. For a Frontier node f, L[f] is length of shortest v → f path using only red nodes (except for f)



4. For a Far-off node b, L[b] = ∞

5. L[v] = 0, L[w] > 0 for w ≠ v



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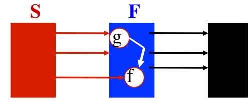
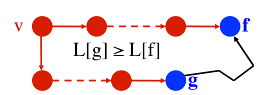
Theorem about the invariant

Settled S **Frontier F** **Far off**





1. For a Settled node s, L[s] is length of shortest v → r path.

2. All edges leaving S go to F.

3. For a Frontier node f, L[f] is length of shortest v → f path using only Settled nodes (except for f).

4. For a Far-off node b, L[b] = ∞. 5. L[v] = 0, L[w] > 0 for w ≠ v

Theorem. For a node **f** in **F** with minimum L value (over nodes in **F**), **L[f]** is the length of the shortest path from **v** to **f**.

Case 1: v is in **S**.

Case 2: v is in **F**. Note that L[v] is 0; it has minimum L value

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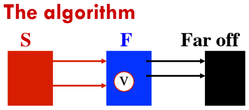
The algorithm



1. **For s, L[s]** is length of shortest v→ s path.
2. **Edges leaving S go to F.**
3. **For f, L[f]** is length of shortest v → f path using red nodes (except for f).
4. **For b in Far off, L[b] = ∞**
5. L[v] = 0, L[w] > 0 for w ≠ v

Theorem: For a node **f** in **F** with min L value, L[f] is shortest path length

For all w, L[w]= ∞;   L[v]= 0;
F= { v }; S= { };

Loopy question 1:
How does the loop start? What is done to truthify the invariant?

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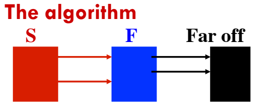
The algorithm



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Theorem: For a node **f** in **F** with min L value, L[f] is shortest path length

For all w, L[w]= ∞;   L[v]= 0;
F= { v }; S= { };
while   F ≠ {} {
}

Loopy question 2:
When does loop stop? When is array L completely calculated?

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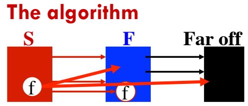
The algorithm



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4. **For b, L[b] = ∞**
5. L[v] = 0, L[w] > 0 for w ≠ v

Theorem: For a node **f** in **F** with min L value, L[f] is shortest path length

For all w, L[w]= ∞;   L[v]= 0;
F= { v }; S= { };
while   F ≠ {} {
  f= node in F with min L value;
  Remove f from F, add it to S;
}

Loopy question 3:
How is progress toward termination accomplished?

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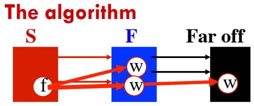
The algorithm



1. **For s, L[s]** is length of shortest v → s path.
2. **Edges leaving S go to F.**
3. **For f, L[f]** is length of shortest v → f path using red nodes (except for f).
4. **For b, L[b] = ∞**
5. L[v] = 0, L[w] > 0 for w ≠ v

Theorem: For a node **f** in **F** with min L value, L[f] is shortest path length

For all w, L[w]= ∞;   L[v]= 0;
F= { v }; S= { };
while   F ≠ {} {
  f= node in F with min L value;
  Remove f from F, add it to S;
  for each edge (f,w) {
    if (L[w] is ∞) add w to F;
    if (L[f] + weight (f,w) < L[w])
      L[w]= L[f] + weight(f,w);
  }
}

Algorithm is finished

Loopy question 4:
How is the invariant maintained?

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Final algorithm

1. No need to implement **S**.
2. Implement **F** as a min-heap.
3. Instead of ∞, use Integer.MAX_VALUE.

For all w, L[w]= ∞; L[v]= 0;
F= { v }; ~~S= { };~~
while F ≠ {} {
  f= node in F with min L value;
  Remove f from F, ~~add it to S;~~
  for each edge (f,w) {
    ~~**if** (L[w] is ∞) add w to F;~~
    ~~**if** (L[f] + weight (f,w) < L[w])~~
      ~~L[w]= L[f] + weight(f,w);~~
    if (L[w] == Integer.MAX_VAL) {
      L[w]= L[f] + weight(f,w);
      add w to F;
    } **else** L[w]= Math.min(L[w], L[f] + weight(f,w));
  }
}

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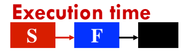
Execution time



n nodes, reachable from v. e ≥ n-1 edges
n–1 ≤ e ≤ n*n

For all w, L[w]= ∞; L[v]= 0;   **O(n)**
F= { v };   **O(1)**
while F ≠ {} {   **O(n)**
  f= node in F with min L value;   **O(n)**
  Remove f from F;   **O(n log n)**
  for each edge (f,w) {   **O(n + e)**
    if (L[w] == Integer.MAX_VAL) {   **O(e)**
      L[w]= L[f] + weight(f,w);   **O(n-1)**
      add w to F;   **O(n log n)**
    }
    else L[w]=   **O((e-(n-1)) log n)**
      Math.min(L[w], L[f] + weight(f,w));
  }
}

outer loop:
n iterations.
Condition evaluated n+1 times.

inner loop:
e iterations.
Condition evaluated n + e times.

Complete graph: $O(n^2 \log n)$. Sparse graph: O(n log n)

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