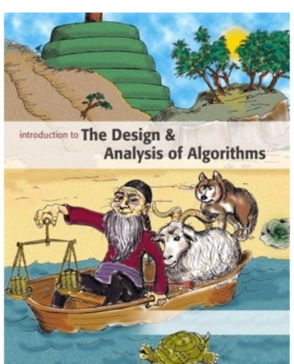
Introduction to

Algorithm Design and Analysis

[15] Path in Graph



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In the last class…

- **Optimization Problem**
  - o Greedy strategy
- **MST Problem**
  - o Prim's Algorithm
  - o Kruskal's Algorithm
- **Single-Source Shortest Path Problem**
  - o Dijstra's Algorithm

Path in Graphs

- **Single-source shortest path**
  - o Dijkstra's algorithm by example
  - o Priority queue-based implemetation
  - o Proof of correctness
- **All-pair shortest path**
  - o Shortest Path and Transitive Closure
  - o Washall's Algorithm for Transitive Closure
  - o All-Pair Shortest Paths
  - o Matrix for Transitive Closure
  - o Multiplying Bit Matrices - Kronrod's Algorithm

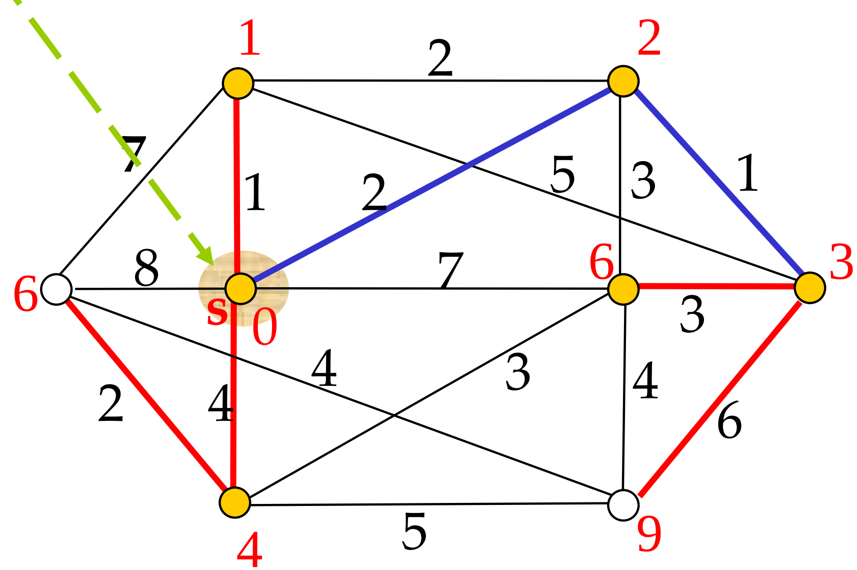
Single Source Shortest Paths

The single source

Red labels on each vertex is the length of the shortest path from s to the vertex.

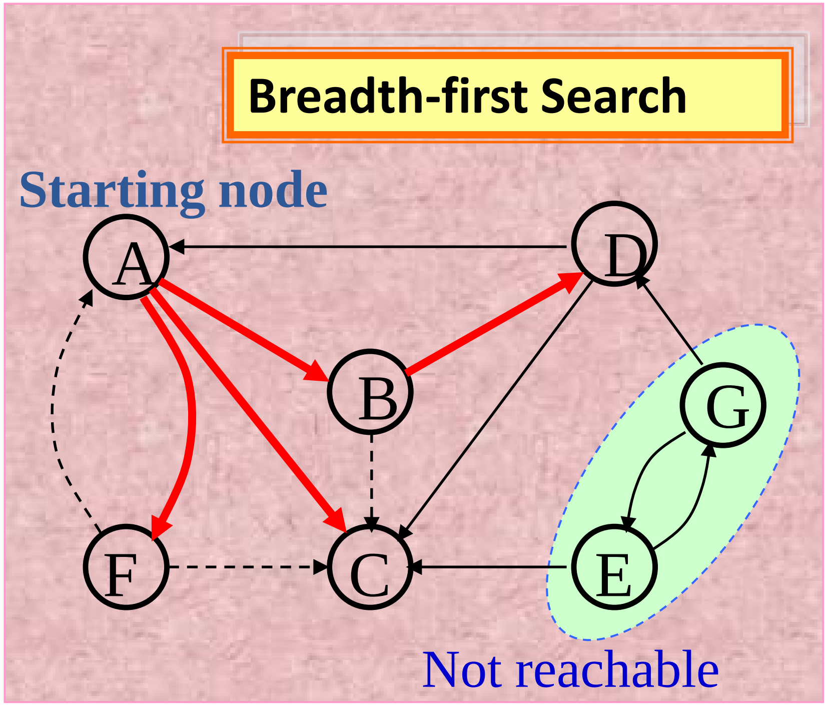
Note:

The shortest [0, 3]-path doesn't contain the shortest edge leaving s, the edge [0,1]

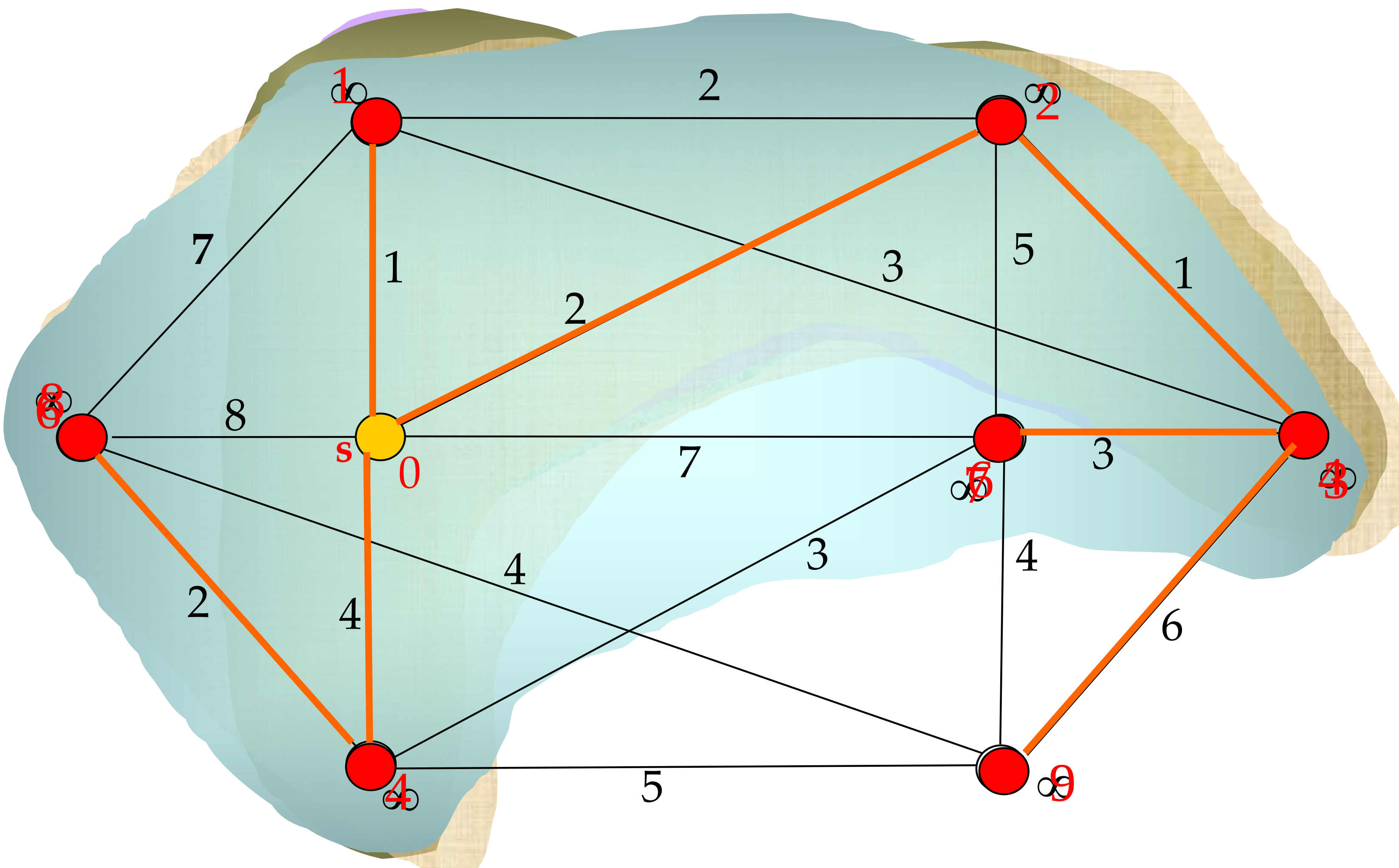


Warm Up

- Single-source shortest path over **uniformly weighted graph**
  - o Just BFS



Dijkstra’s Algorithm



Priority Queue-based Implementation

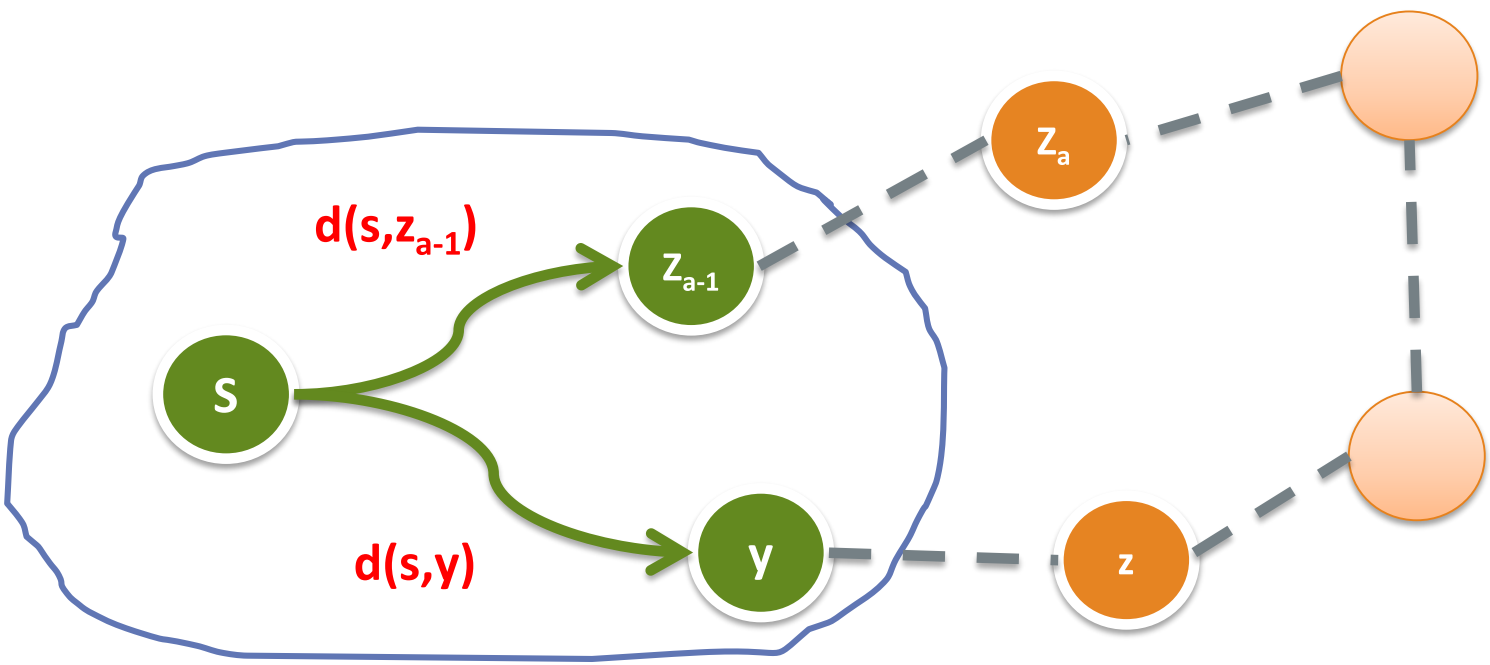
Shortest Paths

```
Void shortestPaths(EdgeList[] adjInfo, int n, int s,
int[] parent, float[]fringeWgt)

   int[] status = new int[n+1];
   MinPQ pq = create(n, status, parent, fringeWgt);

   insert(pq, s, -1, 0);
   while(isEmpty(pq)==false)
      int v = getMin(pq);
      deleteMin(pq);
      updateFringe(pq, adjInfo[v], v);
```

```
void updateFringe(MinPQ pq, EdgeList
adjInfoOfV, int v)

   float myDist = pq.fringeWgt[v];
   EdgeList remAdj;
   remAdj = adjInfoOfV;
   while{remAdj != nil}
      EdgeInfo wInfo = first(remAdj);
      int w = wInfo.to;
      float newDist = myDist + wInfo.weight;
      if(pq.status[w]==unseen)
         insert(pq,w,v,newDist);
      else if(pq.status[w] = fringe)
         if(newDist < getPriority(pq,w))
            decreaseKey(pq,w,v,newDist);
      remAdj = rest(remAdj);
return;
```

Correctness of the Dijkstra's Algorithm

- $W(s\text{->}y\text{->}z) < W(s\text{->}z_{a-1}\text{->}z_a\text{->}z)$



From Algorithm to Skeleton

- **Single-source shortest path (SSSP)**
- **SSSP + node weight constraint**
  - E.g. in routing
    - Each router has a cost (node cost)
    - Each route has a cost (edge cost)
- **SSSP + capacity constraint**
  - The "pipe problem"
  - The "PEV problem"
    - Pure Electric Vehicle

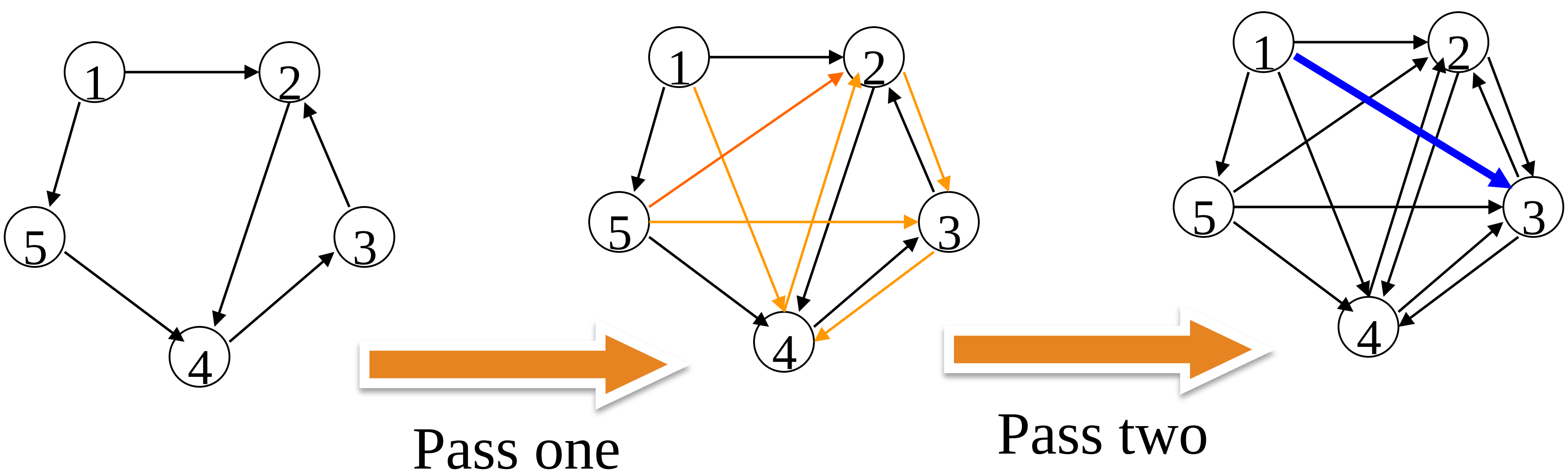
"Dijkstra's Skeleton"

Fundamental Questions

- **For all pair of vertices in a graph, say, *u*, *v*:**
  - Is there a path from *u* to *v*?
  - What is the shortest path from *u* to *v*?
- **Reachability as a (reflexive) transitive closure of the adjacency relation**
  - which can be represented as a bit matrix

Transitive Closure by Shortcuts

- The idea: if there are edges $s_i s_k$, $s_k s_j$, then an edge $s_i s_j$, the "shortcut" is inserted.



Note: the triple (1,5,3) is considered more than once

Shortcut Algorithm

- **Input:** *A*, an $n \times n$ boolean matrix that represents a binary relation
- **Output:** *R*, the boolean matrix for the transitive closure of *A*
- **Procedure**

```
o void simpleTransitiveClosure(boolean[ ][ ] A, int n, boolean[ ][ ] R)
o     int i,j,k;
o     Copy A to R;
o     Set all main diagonal entries, r_ii, to true;
o     while (any entry of R changed during one complete pass)
o         for (i=1; i≤n; i++)
o             for (j=1; j≤n; j++)
o                 for (k=1; k≤n; k++)
o                     r_ij=r_ij∨(r_ik∧r_kj)
```

$O(n^4)$

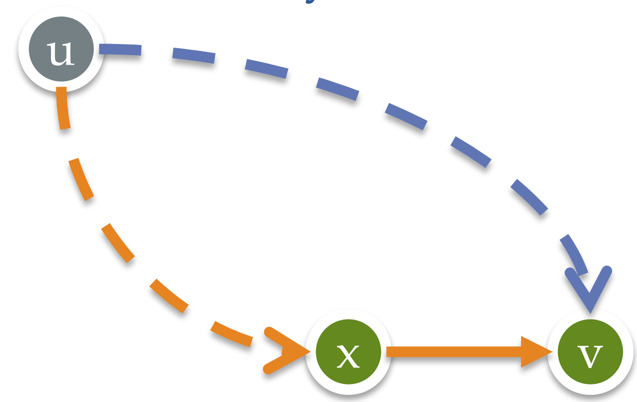
The order of (i,j,k) matters

Another Way to Add Shortcuts

```
SHIMBELAPSP(V, E, w):
  for all vertices u
      for all vertices v
          if u = v
              dist[u, v] ← 0
          else
              dist[u, v] ← ∞
  for k ← 1 to V − 1
      for all vertices u
          for all edges x→v
              if dist[u, v] > dist[u, x] + w(x→v)
                  dist[u, v] ← dist[u, x] + w(x→v)
```

$O(n^2m)$

for every u



for each edge xv

n-1 round iteration

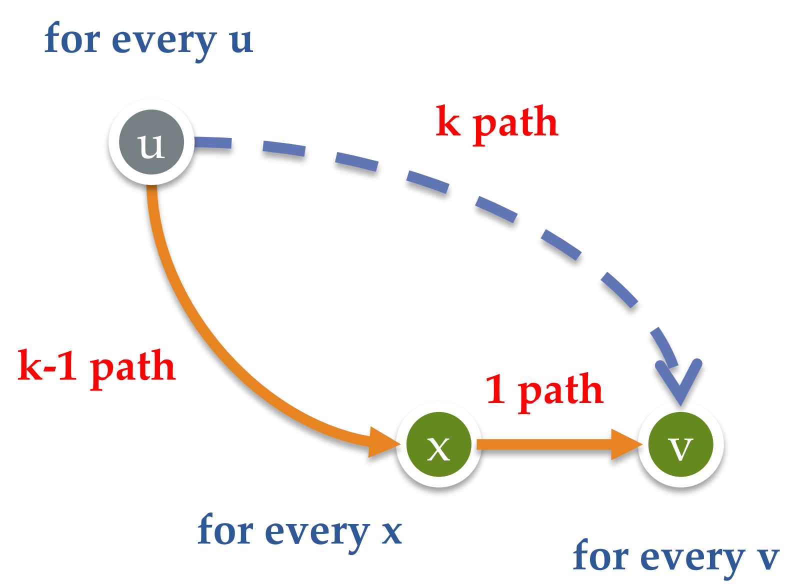
Length of the Path

Length of the shortest path of at most k edges

$$dist(u,v,k) = \begin{cases} 0 & \text{if } u = v \\ \infty & \text{if } k = 0 \text{ and } u \neq v \\ \min\limits_x \left(dist(u,x,k-1) + w(x\to v)\right) & \text{otherwise} \end{cases}$$

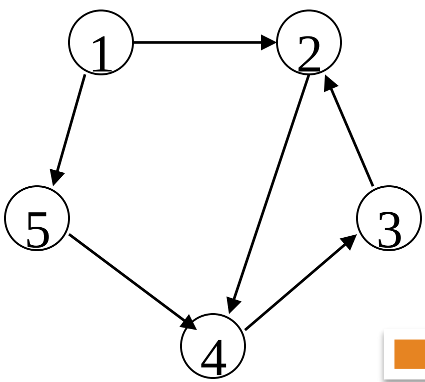
```
APSP(V, E, w):
  for all vertices u
      for all vertices v
          if u = v
              dist[u, v, 0] ← 0
          else
              dist[u, v, 0] ← ∞
  for k ← 1 to V − 1
      for all vertices u
          for all vertices v
              dist[u, v, k] ← ∞
              for all vertices x
                  if dist[u, v, k] > dist[u, x, k − 1] + w(x→v)
                      dist[u, v, k] ← dist[u, x, k − 1] + w(x→v)
```

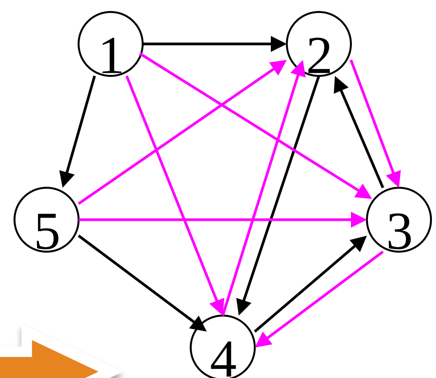
$O(n^4)$



Shortcuts in Different Order

- **Duplicated checking may be deleted by changing the order of the vertices.**





Pass one

Check the vertices in decreasing order.

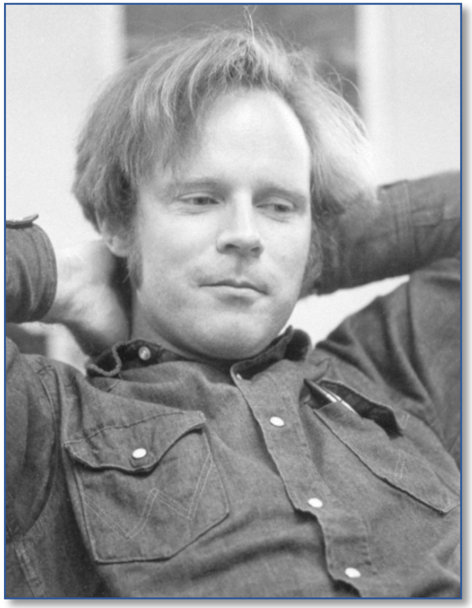
No edge is added in Pass two. End.

Floyd's Lemma

组合问题的优良算法具有巨大回报，这个事实激励了技术水平的突飞猛进。... ... 大约从1970年起，计算机科学家们经历了所谓的‘**Floyd引理**’现象：看似需用n^3次运算的问题实际上可能用$O(n^2)$次运算就能求解，看似需用n^2次运算的问题实际上可能用O(nlogn)次运算就能处理，而且nlogn通常还可以减少到O(n)。一些更难的问题的运行时间也从$O(2^n)$减少到$O(1.5^n)$，再减少到$O(1.3^n)$，等等。

\- Knuth, Volumn4A, TAOCP

Robert W Floyd, In Memoriam
by Donald E. Knuth, Stanford University



Change the Order: Floyd-Warshall's Algorithm

- **void** simpleTransitiveClosure(**boolean**[][] A, **int** n, **boolean**[][] R)
- **int** i,j,k;
- Copy A to R;
- Set all main diagonal entries, r_{ii}, to *true*;
- ~~**while** (any entry of R changed during one complete pass)~~
- **for** (k=1; k≤n; k++)
- **for** (i=1; i≤n; i++)
- **for** (j=1; j≤n; j++)
- $r_{ij}=r_{ij}\vee(r_{ik}\wedge r_{kj})$

k varys in the outmost loop

Note: "false to true" can not be reversed

Correctness of Warshall's Algorithm

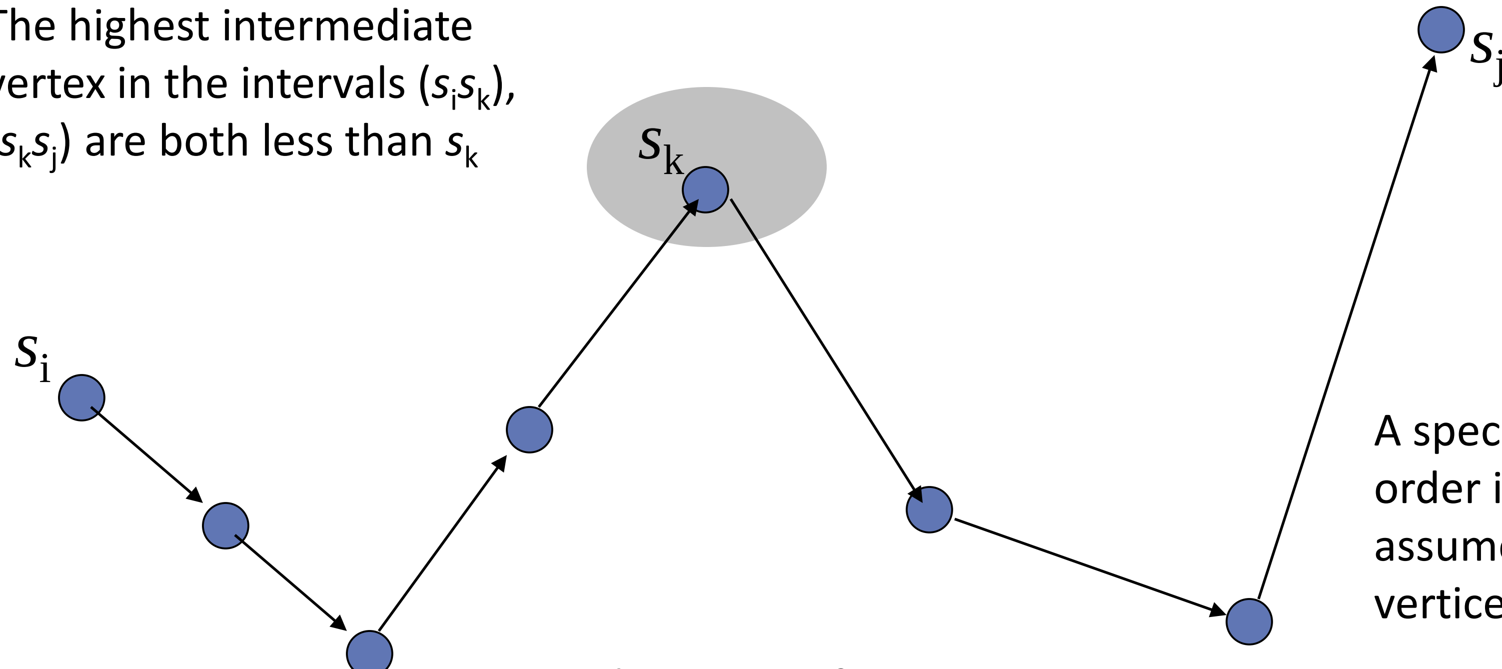
- **Notation:**
  - The value of r_{ij} changes during the execution of the body of the "**for** *k*…" loop
    - After initializations: $\boldsymbol{r_{ij}^{(0)}}$
    - After the k^{th} time of execution: $\boldsymbol{r_{ij}^{(k)}}$

Correctness of Washall's Algorithm

- **If there is a simple path from s_i to s_j(i≠j) for which the highest-numbered intermediate vertex is s_k, then $r_{ij}^{(k)}$=true.**
- **Proof by induction:**
  - Base case: $r_{ij}^{(0)}$=true if and only if $s_i s_j \in E$
  - Hypothesis: the conclusion holds for h<k(h≥0)
  - Induction: the simple $s_i s_j$-path can be looked as $s_i s_k$-path+$s_k s_j$-path, with the indices h_1, h_2 of the highest-numbered intermediate vertices of both segment **strictly**(simple path) less than k. So, $r_{ik}^{(h1)}$=true, $r_{kj}^{(h2)}$=true, then $r_{ik}^{(k-1)}$=true, $r_{kj}^{(k-1)}$=true(Remember, false to true can not be reversed). So, $r_{ij}^{(k)}$=true

Highest-numbered Intermediate Vertex

The highest intermediate vertex in the intervals $(s_i s_k)$, $(s_k s_j)$ are both less than s_k



A specific order is assumed for all vertices

Vertical position of vertices reflect their vertex numbers

$$r_{ij}=r_{ij}\vee(r_{ik}\wedge r_{kj})$$

Correctness of Washall's Algorithm

- **If there is *no* path from s_i to s_j, then r_{ij}=*false*.**
- **Proof**
  - If r_{ij}=*true*, then only two cases:
  - r_{ij} is set by initialization, then $s_i s_j \in E$
  - Otherwise, r_{ij} is set during the k^{th} execution of (**for** k=1,2,…) when $r_{ik}^{(k-1)}$=true, $r_{kj}^{(k-1)}$=true, which, recursively, leading to the conclusion of the existence of a $s_i s_j$-path. (Note: If a $s_i s_j$-path exists, there exists a simple $s_i s_j$-path)

All-pairs Shortest Path

- **Shortest path property**
  - If a shortest path from x to z consisting of path P from x to y followed by path Q from y to z. Then P is a shortest xy-path, and Q, a shortest yz-path.
- **The regular matrix representing a graph can easily be transformed into a (minimum) distance matrix D**

(just replacing 1 by edge weight, 0 by infinity, and setting main diagonal elements as 0)

Computing the Distance Matrix

- **Basic formula:**
  - $D^{(0)}[i][j]=w_{ij}$
  - $D^{(k)}[i][j]=\min(D^{(k-1)}[i][j], D^{(k-1)}[i][k]+ D^{(k-1)}[k][j])$

- **Basic property:**
  - $D^{(k)}[i][j]\leq d_{ij}^{(k)}$

    where $d_{ij}^{(k)}$ is the weight of a shortest path from v_i to v_j with highest numbered intermediate vertex v_k.

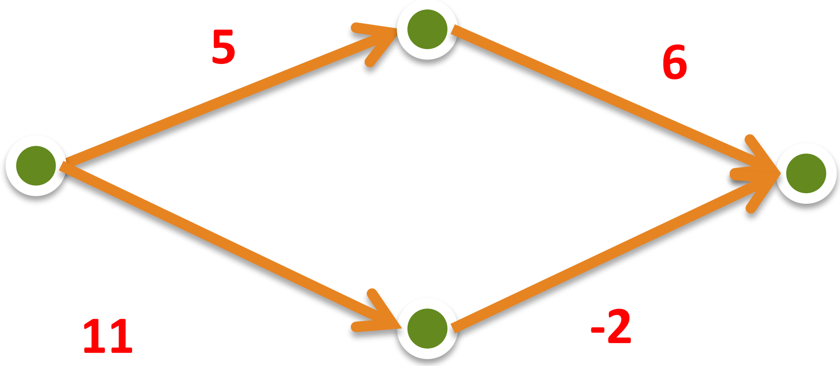
All-Pairs Shortest Paths

- **Floyd algorithm**
  - Only slight changes on Washall's algorithm.

```
Void allPairsShortestPaths(float [][] W, int n, float [][] D)
   int i, j, k;
   Copy W into D;
   for (k=1; k≤n; k++)
      for (i=1; i≤n; i++)
         for (j=1; j≤n; j++)
            D[i][j] = min (D[i][j], D[i][k]+D[k][j];
```

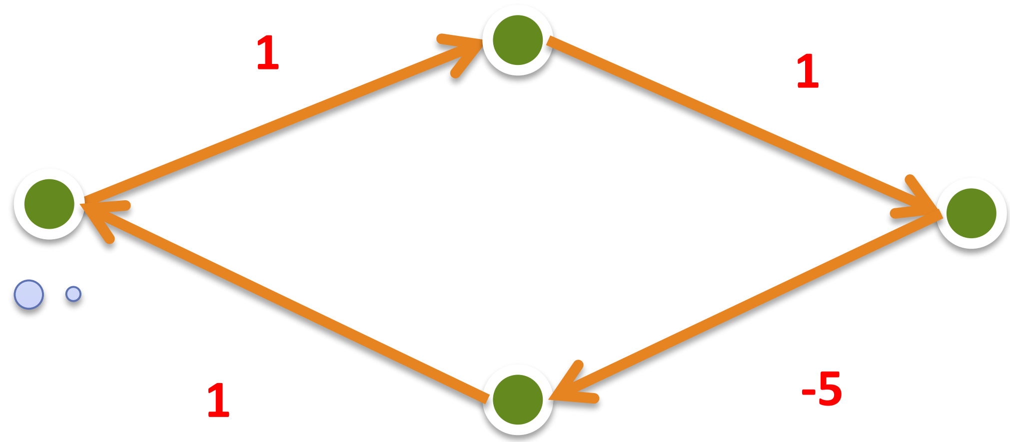
- **Routing table tracking the path**

Negative Weight



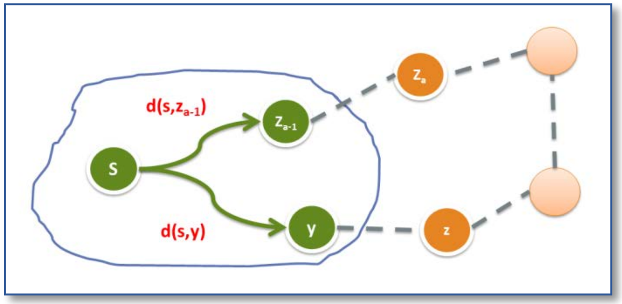
“shortest path” is not well defined

Negative weight cycle

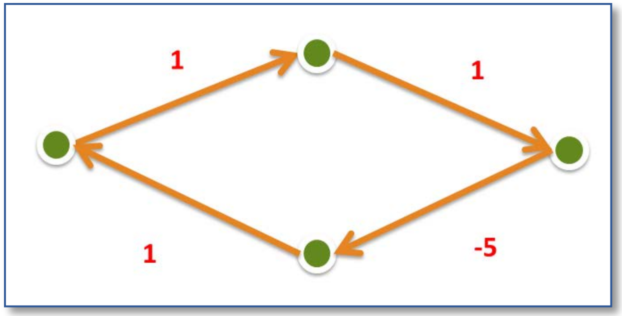


Negative Weight

- **Can the shortest path algorithm work correctly?**
  - o Dijkstra's algorithm
    - No negative weight edge



  - o Floyed's algorithm
    - No negative weight cycle



Matrix Representation

- **Define family of matrix $A^{(p)}$:**
  - $a_{ij}^{(p)}=true$ if and only if there is a path of length p from s_i to s_j.
- **$A^{(0)}$ is specified as identity matrix. $A^{(1)}$ is exactly the adjacency matrix.**
- **Note that $a_{ij}^{(2)}=true$ if and only if exists some s_k, such that both $a_{ik}^{(1)}$ and $a_{kj}^{(1)}$ are *true*. So, $a_{ij}^{(2)}=\bigvee_{k=1,2,\ldots,n} (a_{ik}^{(1)} \wedge a_{kj}^{(1)})$, which is an entry in the *Boolean matrix product*.**

Boolean Matrix Operations

- **Boolean matrix product C=AB as:**
  - o $c_{ij}=\vee_{k=1,2,\ldots,n}(a_{ik}\wedge b_{kj})$
- **Boolean matrix sum D=A+B as:**
  - o $d_{ij}=a_{ij}\vee b_{ij}$
- ***R*, the transitive closure matrix of *A*, is the sum of all A^p, *p* is a non-negative integer.**
- **For a digraph with *n* vertices, the length of the longest simple path is no larger than *n*-1.**

Bit Matrix

- A **bit string** of length n is a sequence of n bits occupying contiguous storage(word boundary) (usually, n is larger than the word length of a computer)
- If A is a **bit matrix** of $n \times n$, then $A[i]$ denotes the ith row of A which is a bit string of length n. a_{ij} is the jth bit of $A[i]$.
- The **procedure** **bitwiseOR(a,b,n)** compute $a \vee b$ bitwise for n bits, leaving the result in a.

Straightforward Multiplication of Bit Matrix

- **Computing** $C=AB$
  - <Initialize C to the zero matrix>
  - **for** (i=1; i≤n, i++)
  - **for** (k=1; k≤n, k++)
  - **if** (a_{ik}==*true*) bitwiseOR($C[i]$, $B[k]$, n)

Thought as a union of sets (row union), n^2 unions are done at most

In the case of a_{ik} is *true*, $c_{ij}=a_{ik}b_{kj}$ is true iff. b_{kj} is true. As a result: $C[i]=\cup_{k\in A[i]}B[k]$, $(A[i]=\{k\,|\,a_{ik}=true\})$

Union for B[k] is **repeated each time** when the kth bit is *true* in a different row of A is encountered.

Reducing the Duplicates by Grouping

- **Multiplication of *A*, *B*, two 12×12 matrices**

$$\begin{array}{c} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \\ A_7 \\ A_8 \\ A_9 \\ A_{10} \\ A_{11} \\ A_{12} \end{array}
\begin{pmatrix}
1&0&1&1&0&1&0&1&0&0&0&1\\
&&&&&&&&&&&\\
1&0&1&1&1&0&0&1&1&0&1&1\\
&&&&&&&&&&&\\
&&&&&&&&&&&\\
&&&&0&1&0&1&&&&\\
1&0&1&1&1&0&0&1&1&1&1&0\\
&&&&&&&&&&&\\
&&&&&&&&&&&\\
&&&&&&&&&&&\\
&&&&&&&&&&&\\
&&&&&&&&&&&
\end{pmatrix}$$

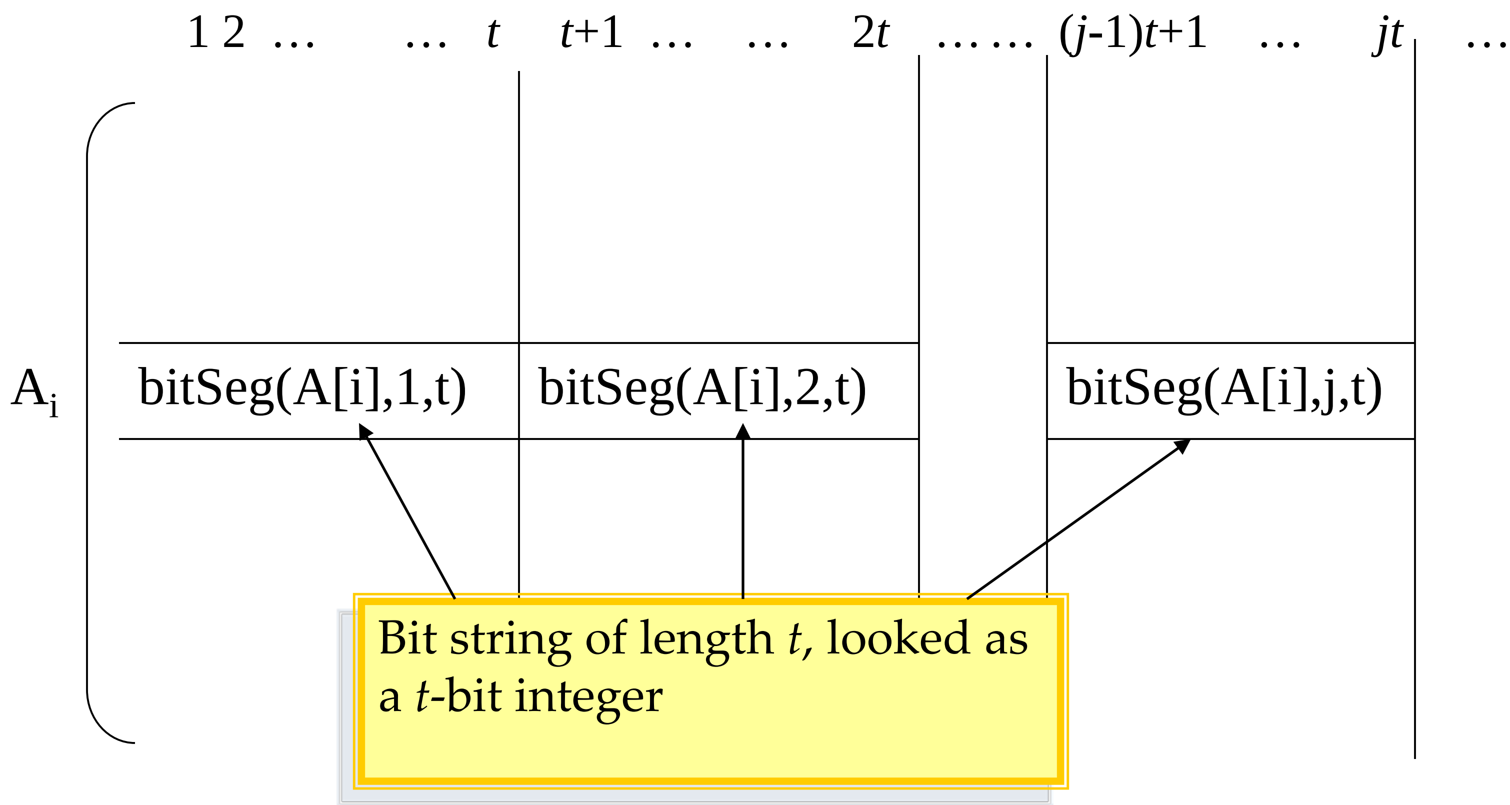
Segment

Length t

- 12 rows of B are divided evenly into 3 groups, with rows 1-4 in group 1, etc.
- With each group, all possible unions of different rows are pre-computed. (This can be done with 11 unions if suitable order is assumed.)
- When the first row of AB is computed, ($B[1]\cup B[3]\cup B[4]$) is used in stead of 3 different unions, and this combination is used in computing the 3rd and 7th rows as well.

The Segmentation for Matrix A

The $n \times n$ array



An Example

	Group 1 $(1\ldots t)$				Group 2 $(t+1\ldots 2t)$				Group 3 $(2t+1\ldots 3t)$			
A_1	1	0	1	1	0	1	0	1	0	0	0	1
A_2	1	0	0	0	1	0	1	1	0	0	1	0
A_3	1	0	1	1	1	0	0	1	1	0	1	1
A_4	0	1	1	0	0	0	1	0	1	0	1	0
A_5	0	1	0	0	1	1	0	1	0	1	0	1
A_6	1	1	0	1	0	1	0	1	1	0	1	0
A_7	1	0	1	1	1	0	0	1	1	1	1	0
A_8	1	1	1	1	0	0	1	1	0	1	1	0
A_9	0	1	1	0	1	0	1	0	1	1	1	0
A_{10}	1	0	0	0	1	0	1	1	0	0	1	1
A_{11}	0	1	0	1	0	1	0	1	0	1	0	0
A_{12}	1	0	0	1	0	0	1	0	1	0	0	0

$t=4$

bitSeg($A[7], 1, t$)

$= 1011_2 = 11$

B_1, B_2, B_3, B_4	any union combination of $\{B_1,B_2,B_3,B_4\}$, totaling 16, 11 computed	**Group 1 $(1\ldots t)$**
B_5, B_6, B_7, B_8	any union combination of $\{B_5,B_6,B_7,B_8\}$, totaling 16, 11 computed	**Group 2 $(t+1\ldots 2t)$**
$B_9, B_{10}, B_{11}, B_{12}$	any union combination of $\{B_9,B_{10},B_{11},B_{12}\}$, totaling 16, 11 computed	**Group 3 $(2t+1\ldots 3t)$**

Where to store?

Storage of the Row Combinations

- **Using one large 2-dimensional array**
- **Goals**
  - keep all unions generated
  - provide indexing for using
- **Coding within a group**
  - One-to-one correspondence between a bit string of length t and one union for a subset of a set of t elements
- **Establishing indexing for union required**
  - When constructing a row of AB, a segment can be notated as a integer. Use it as index.

Storage the Unions

allUnion

one row for
one group

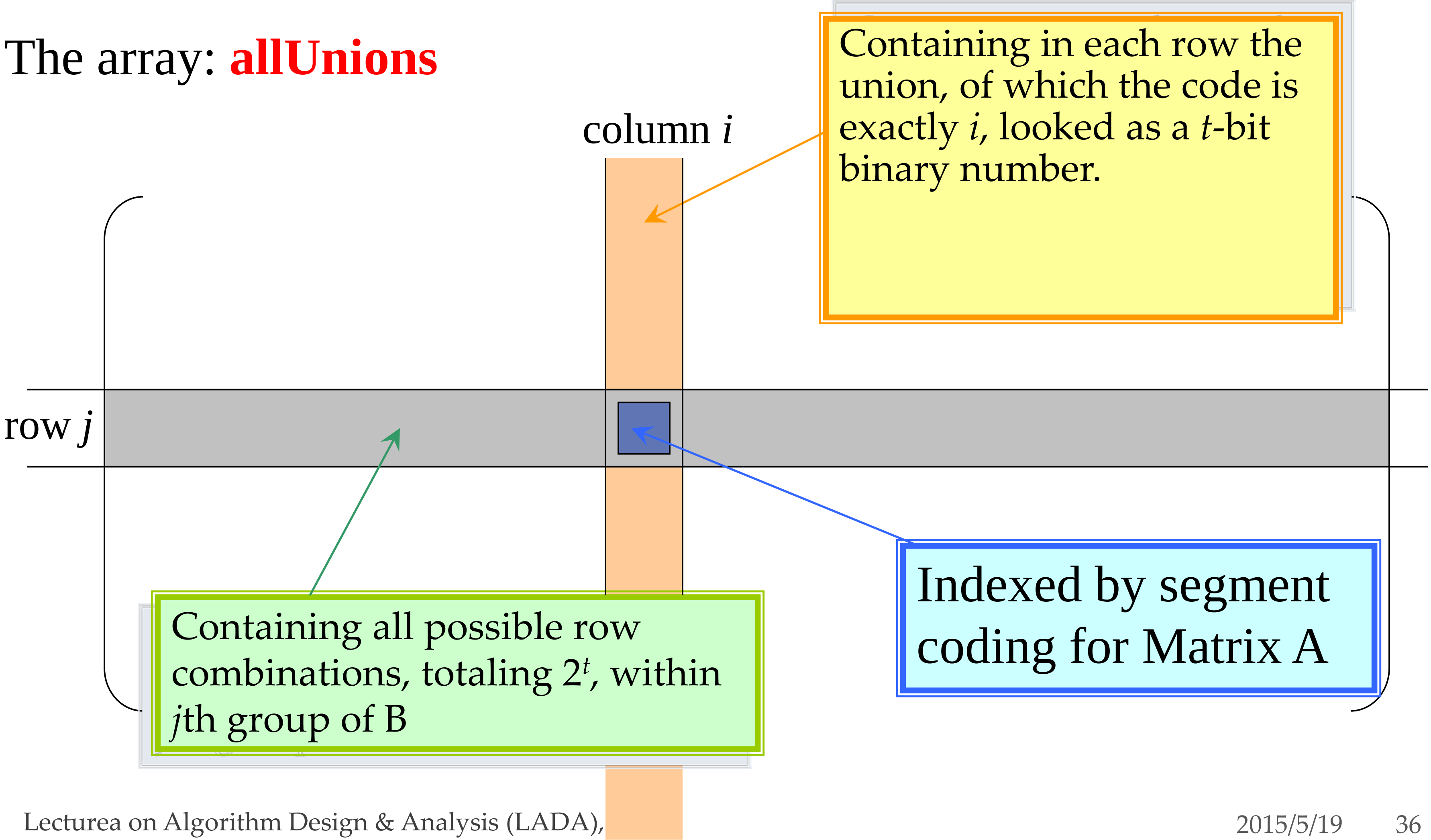
column indexed by bitSeg(A[i],j,t)

$$\begin{bmatrix} \phi & 4 & 3 & 3,4 & 2 & 2,4 & 2,3 & 2,3,4 & 1 & 1,4 & 1,3 & 1,3,4 & 1,2 & 1,2,4 & 1,2,3 & 1,2,3,4 \\ \phi & 8 & 7 & 7,8 & 6 & 6,8 & & & & & \cdots\cdots & & & & & \\ \phi & 12 & 11 & 11,12 & 10 & 10,12 & & & & & & & & & & \end{bmatrix}$$

i,j,k stands for $B_i \cup B_j \cup B_k$

Array for Row Combinations

The array: **allUnions**



Cost as Function of Group Size

- **Cost for the pre-computation**
  - There are 2^t different combination of rows in one group, including an empty and t singleton. Note, in a suitable order, each combination can be made using only one union. So, the total number of union is **$g[2^t-(t+1)]$**, where $g=n/t$ is the number of group.
- **Cost for the generation of the product**
  - In computing one of n rows of AB, at most one combination from each group is used. So, the total number of union is **$n(g-1)$**

Selecting Best Group Size

- **The total number of union done is:**

  $$g[2^t-(t+1)]+n(g-1) \approx (n2^t)/t+n^2/t$$ **(Note: $g=n/t$)**

- **Trying to minimize the number of union**
  - Assuming that the first term is of higher order:
    - Then $t \geq \lg n$, and the least value is reached when $t=\lg n$.
  - Assuming that the second term is of higher order:
    - Then $t \leq \lg n$, and the least value is reached when $t=\lg n$.
- **So, when $t \approx \lg n$, the number of union is roughly $2n^2/\lg n$, which is of lower order than n^2. We use $t=\lfloor \lg n \rfloor$**

For symplicity, exact power for n is assumed

Sketch for the Procedure

- t=$\lfloor \lg n \rfloor$; g=$\lceil n/t \rceil$;
- <Compute and store in allUnions unions of all combinations of rows of *B*>
- for (i=1; i≤*n*; i++)
-     <Initialize C[i] to 0>
-     for (j=1; j≤*g*; j++)
-         C[i] = C[i] ∪ allUnions[j][bitSeg(A[i],j,t)]

Kronrod Algorithm

- **Input: A,B and n, where A and B are n×n bit matrices.**
- **Output: C, the Boolean matrix product.**
- **Procedure**
  - The processing order has been changed, from "row by row" to "group by group", resulting the reduction of storage space for unions.

Complexity of the Kronrod Algorithm

- For computing all unions within a group, 2^t-1 union operations are done.
- One union is bitwiseOR'ed to n row of C
- So, altogether, $(n/t)(2^t-1+n)$ row unions are done.
- The cost of row union is $\lceil n/w \rceil$ bitwise or operations, where w is word size of bitwise or instruction dependent constant.

Thank you!

Q & A

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