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GRID ROUTING

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Introduction

- In the VLSI design cycle, *routing* follows *cell placement*.
- Once routing is completed, precise paths are defined on the layout surface, on which conductors carrying electrical signals are run.
- Routing takes up almost 30% of the design time, and a large percentage of layout area.
  - One main objective is to minimize the area required for routing.

Types of Routing?

- Given a set of blocks placed on a layout surface and defined pin locations:
  - Given a set of obstacles and a set of pins to connect, determine a solution to interconnect the pins on a single layer (**GRID ROUTING**).
  - Determine the approximate regions through which each interconnection net should pass (**GLOBAL ROUTING**).
  - For each routing region, complete the interconnection by assigning horizontal and vertical metal line segments on the layout surface (**DETAILED ROUTING**).

The General Routing Problem

- Given:
  - A set of blocks with pins on the boundaries.
  - A set of signal nets.
  - Locations of the blocks on the layout surface.
- Objective:
  - Find suitable paths on the available layout space, on which wires are run to connect the desired set of pins.
  - Minimize some given objective function, subject to given constraints.

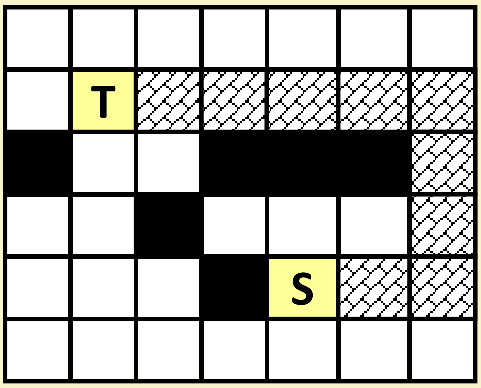
- Types of constraints:
  - Minimum width of routing wires.
  - Minimum separation between adjacent wires.
  - Number of routing layers available.
  - Timing constraints.

GRID ROUTING

Basic Concept

- The layout surface is assumed to be made up of a rectangular array of grid cells.
- Some of the grid cells act as obstacles.
  – Blocks that are placed on the surface.
  – Some nets that are already laid out.
- Objective is to find out a single-layer path (sequence of grid cells) for connecting two points belonging to the same net.

- Two broad classes of grid routing algorithms:
  1. Maze routing algorithms.
  2. Line search algorithms.



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Grid Routing Algorithms

1. Maze running algorithm
   - Lee's algorithm
   - Hadlock's algorithm
2. Line search algorithm
   - Mikami-Tabuchi's algorithm
   - Hightower's algorithm
3. Steiner tree algorithm

Maze Running Algorithms

- The entire routing surface is represented by a 2-D array of grid cells.
  - All pins, wires and edges of bounding boxes that enclose the blocks are aligned with respect to the grid lines.
  - The segments on which wires run are also aligned.
  - The size of grid cells is appropriately defined.
    - Wires belonging to different nets can be routed through adjacent cells without violating the width and spacing rules.
- Maze routers connect a single pair of points at a time.
  - By finding a sequence of adjacent cells from one point to the other.

Lee's Algorithm

- The most common maze routing algorithm.
- Characteristics:
  - If a path exists between a pair of points S and T, it is definitely found.
  - It always finds the shortest path.
  - Uses breadth-first search.
- Time and space complexities are $O(N^2)$ for a grid of dimension $N \times N$.

Phase 1 of Lee's Algorithm

- Wave propagation phase
  - Iterative process.
  - During step i, non-blocking grid cells at Manhattan distance of i from grid cell S are all labeled with i.
  - Labeling continues until the target grid cell T is marked in step L.
    - L is the length of the shortest path.
  - The process fails if:
    - T is not reached and no new grid cells can be labeled during step i.
    - T is not reached and i equals M, some upper bound on the path length.

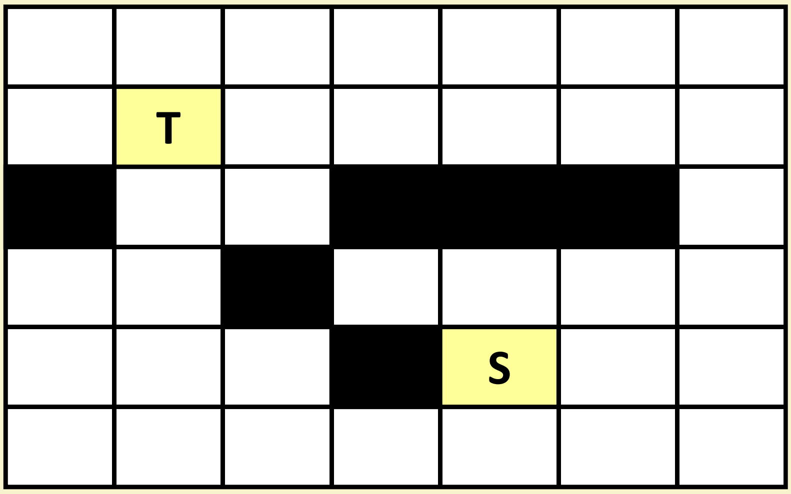
Phase 2 of Lee's Algorithm

- Retrace phase
  - Systematically backtrack from the target cell T back towards the source cell S.
  - If T was reached during step i, then at least one grid cell adjacent to it will be labeled i-1, and so on.
  - By tracing the numbered cells in descending order, we can reach S following the shortest path.
    - There is a choice of cells that can be made in general.
    - In practice, the rule of thumb is not to change the direction of retrace unless one has to do so.
    - Minimizes number of bends.

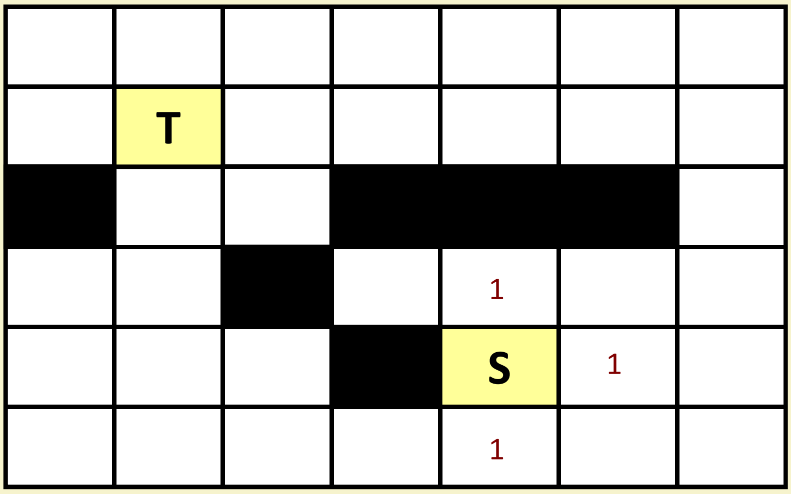
Phase 3 of Lee's Algorithm

- Label clearance
  - All labeled cells except those corresponding to the path just found are cleared.
  - Cells along the path are marked as obstacles.
  - Search complexity is as involved as the wave propagation step itself.

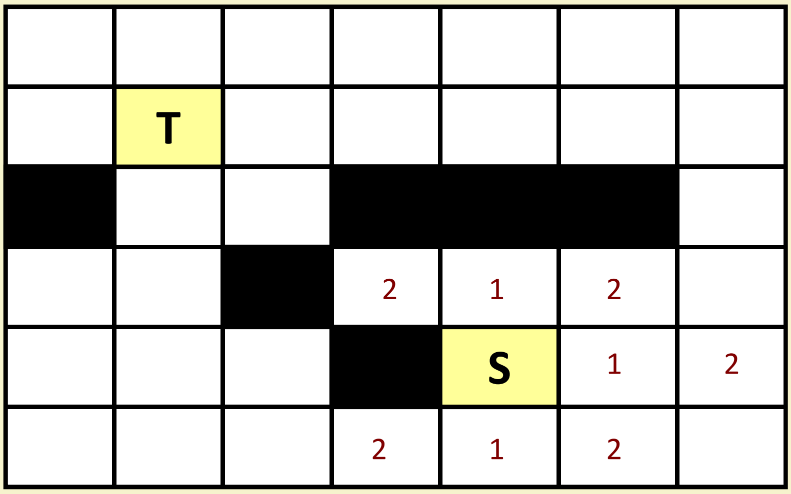
Initial routing problem



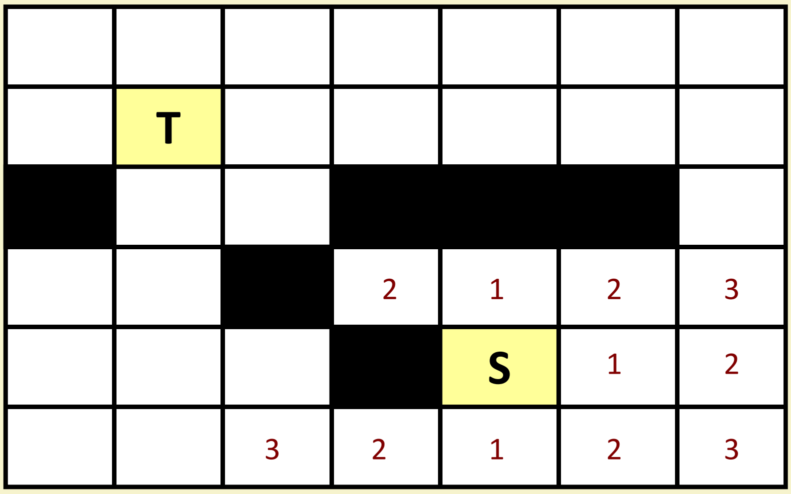
Phase 1 (i = 1)



Phase 1
(i = 2)



Phase 1
(i = 3)



Phase 1
(i = 4)

	T					
						4
			2	1	2	3
		4		S	1	2
	4	3	2	1	2	3

Phase 1
(i = 5)

	T					5
						4
			2	1	2	3
	5	4		S	1	2
5	4	3	2	1	2	3

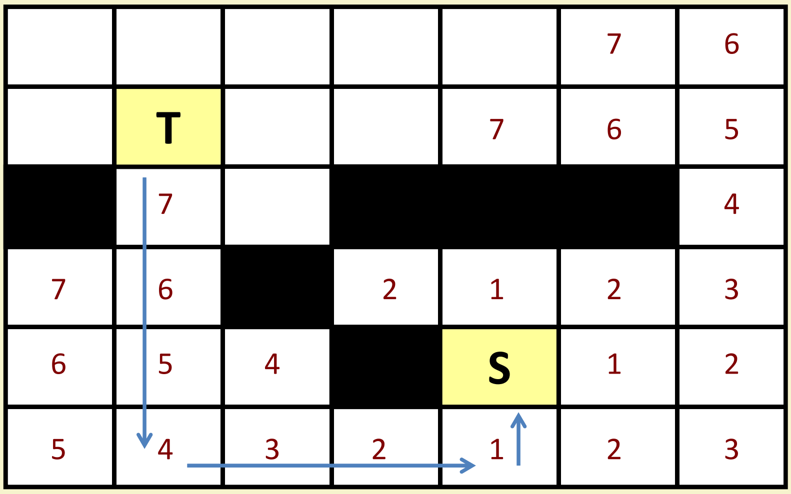
Phase 1
(i = 6)

						6
	T				6	5
						4
	6		2	1	2	3
6	5	4		S	1	2
5	4	3	2	1	2	3

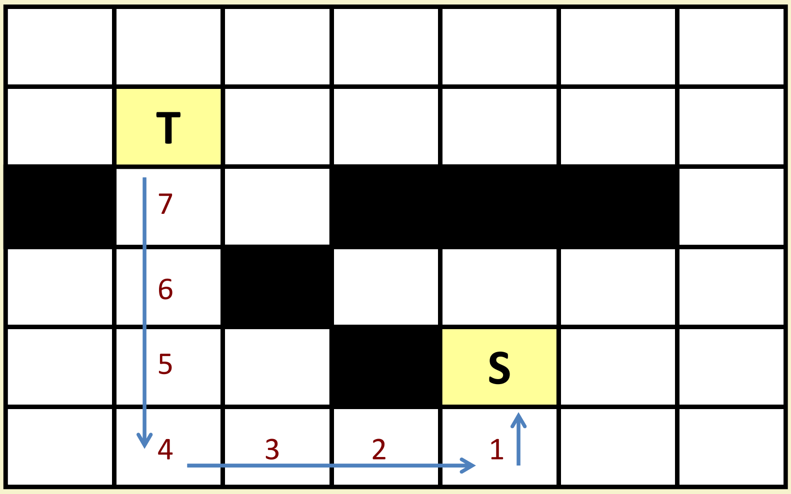
Phase 1
(i = 7)

					7	6
	T			7	6	5
	7					4
7	6		2	1	2	3
6	5	4		S	1	2
5	4	3	2	1	2	3

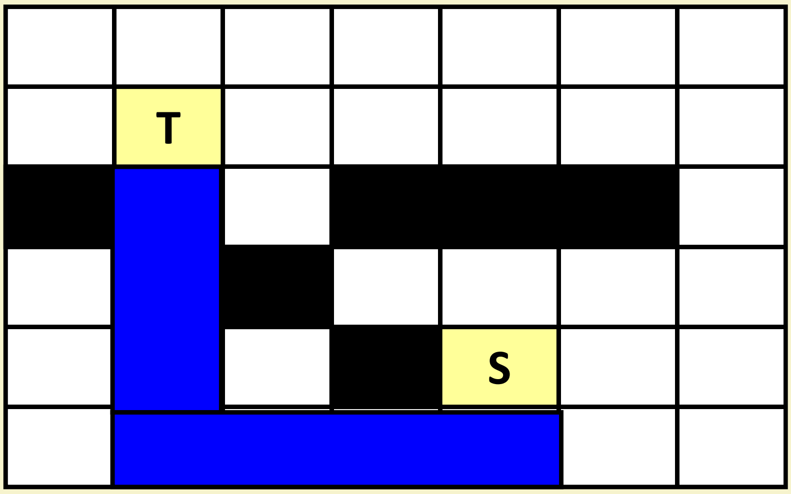
Phase 2 (RETRACE)

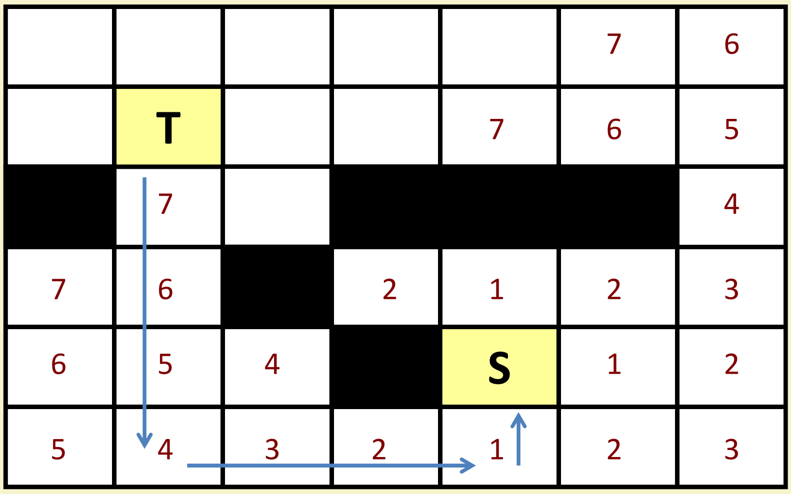


Phase 3 (CLEAR)



Phase 3 (MARK)





- Memory Requirement
  - Each cell needs to store a number between 1 and L, where L is some bound on the maximum path length.
    - For M x N grid, L can be at most M+N-1.
  - One bit combination to denote empty cell.
  - One bit combination to denote obstacles.

$\lceil \log_2(L+2) \rceil$ bits per cell

- Examples:
  1. 2000 x 2000 grid
     - B = $\log_2 4001$ = 12
     - Memory required = 2000 x 2000 x 12 bits = 6 Mbytes
  2. 3000 x 3000 grid
     - B = $\log_2 6001$ = 13
     - Memory required = 3000 x 3000 x 13 bits = 14.6 Mbytes
  3. 4000 x 4000 grid
     - B = $\log_2 8001$ = 13
     - Memory required = 4000 x 4000 x 13 bits = 26 Mbytes

- <u>Improvements</u>:
  - Instead of using the sequence 1,2,3,4,5,..... for numbering the cells, the sequence 1,2,3,1,2,3,... is used.
    - For a cell, labels of predecessors and successors are different. So tracing back is easy.

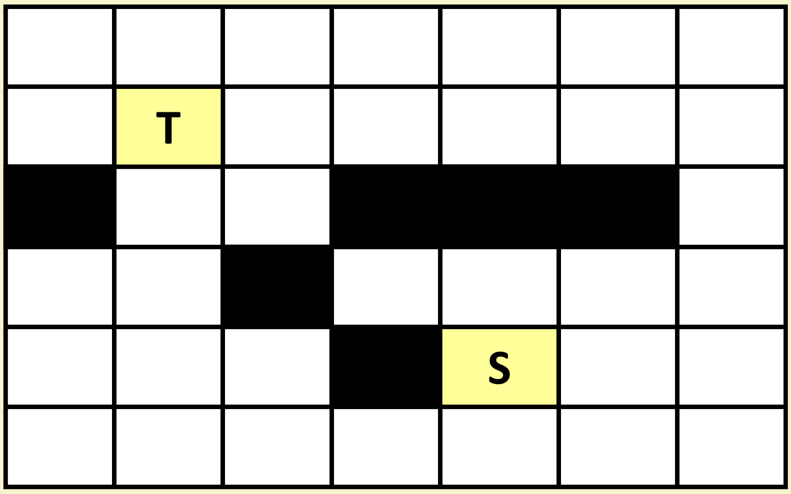
      $\lceil \log_2(3+2) \rceil$ = 3 bits per cell.

      1.5 Mbytes for 2000 x 2000 grid
  - Use the sequence 0,0,1,1,0,0,1,1,.....
    - Predecessors and successors are again different.

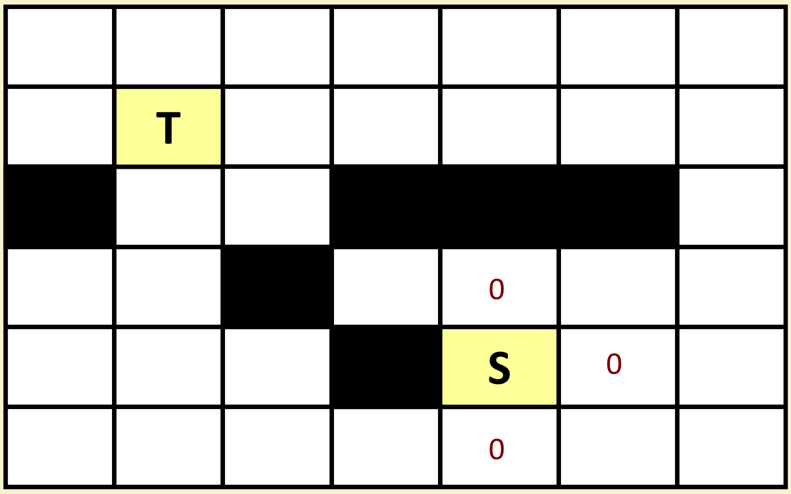
      $\lceil \log_2(2+2) \rceil$ = 2 bits per cell.

      1.0 Mbyte for 2000 x 2000 grid

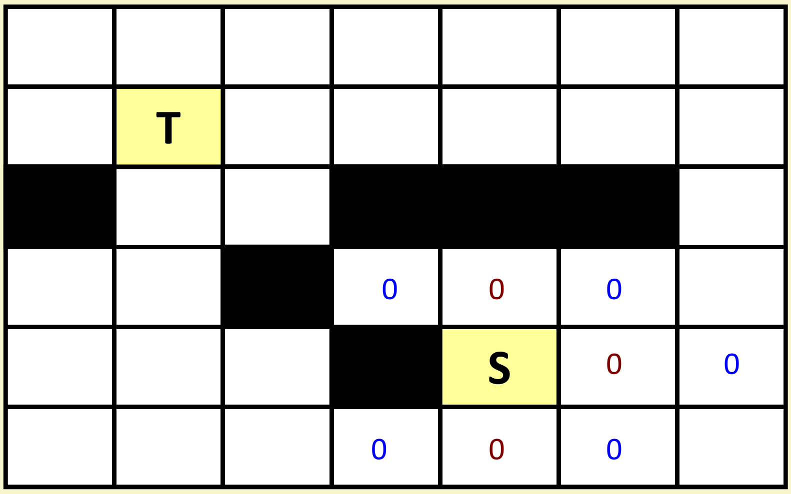
Initial routing problem



Label
0



Label
00



Label
001

	T					
			0	0	0	1
				S	0	0
		1	0	0	0	1

Label
0011

	T					
						1
			0	0	0	1
		1		S	0	0
	1	1	0	0	0	1

Label
0011001

					1	0
	T			1	0	0
	1					1
1	0		0	0	0	1
0	0	1		S	0	0
0	1	1	0	0	0	1

Retrace
0011001

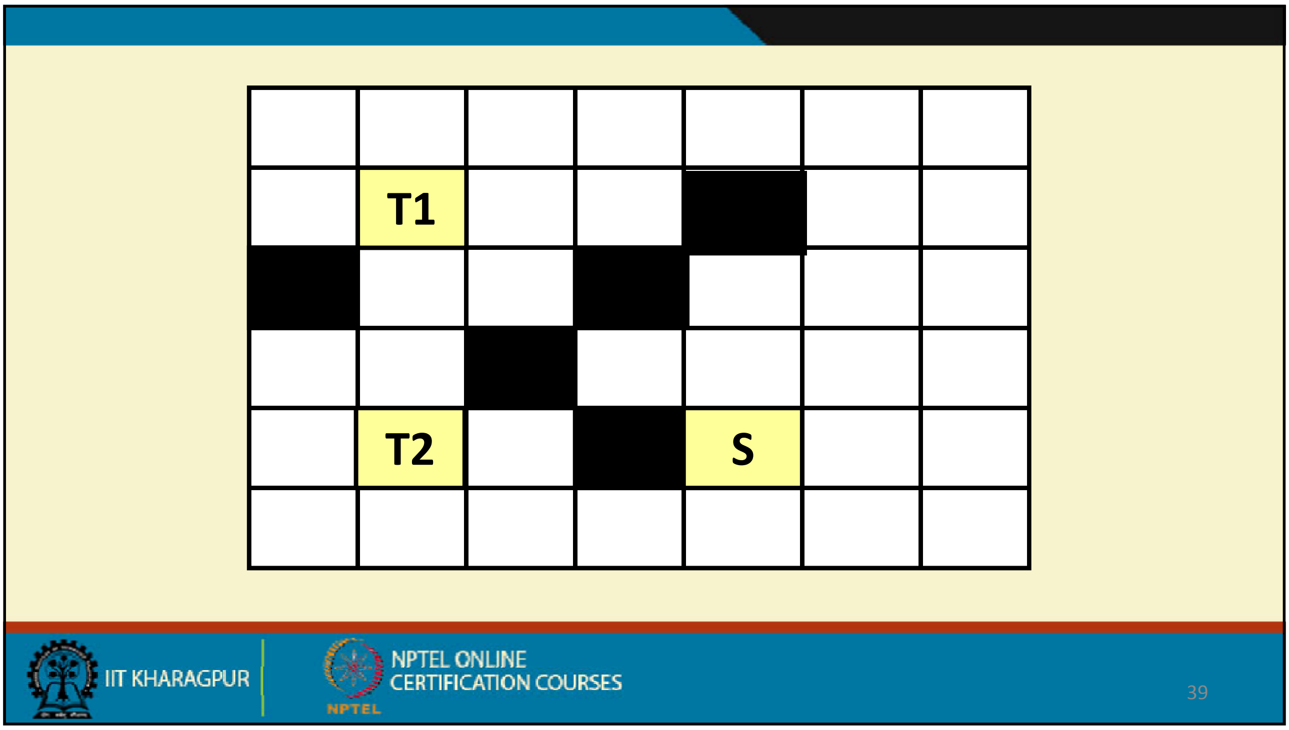
					1	0
	T			1	0	0
	1					1
1	0		0	0	0	1
0	0	1		S	0	0
0	1	1	0	0	0	1

Reducing Running Time

- Starting point selection
  - Choose the starting point as the one that is farthest from the center of the grid.
- Double fan-out
  - Propagate waves from both the source and the target cells.
  - Labeling continues until the wavefronts touch.
- Framing
  - An artificial boundary is considered outside the terminal pairs to be connected.
  - 10-20% larger than the smallest bounding box.

Connecting Multi-point Nets

- A multi-pin net consists of three or more terminal points to be connected.
- Extension of Lee's algorithm:
  - One of the terminals of the net is treated as source, and the rest as targets.
  - A wave is propagated from the source until one of the targets is reached.
  - All the cells in the determined path are next labeled as source cells, and the remaining unconnected terminals as targets.
  - Process continues.


T1
T2
S
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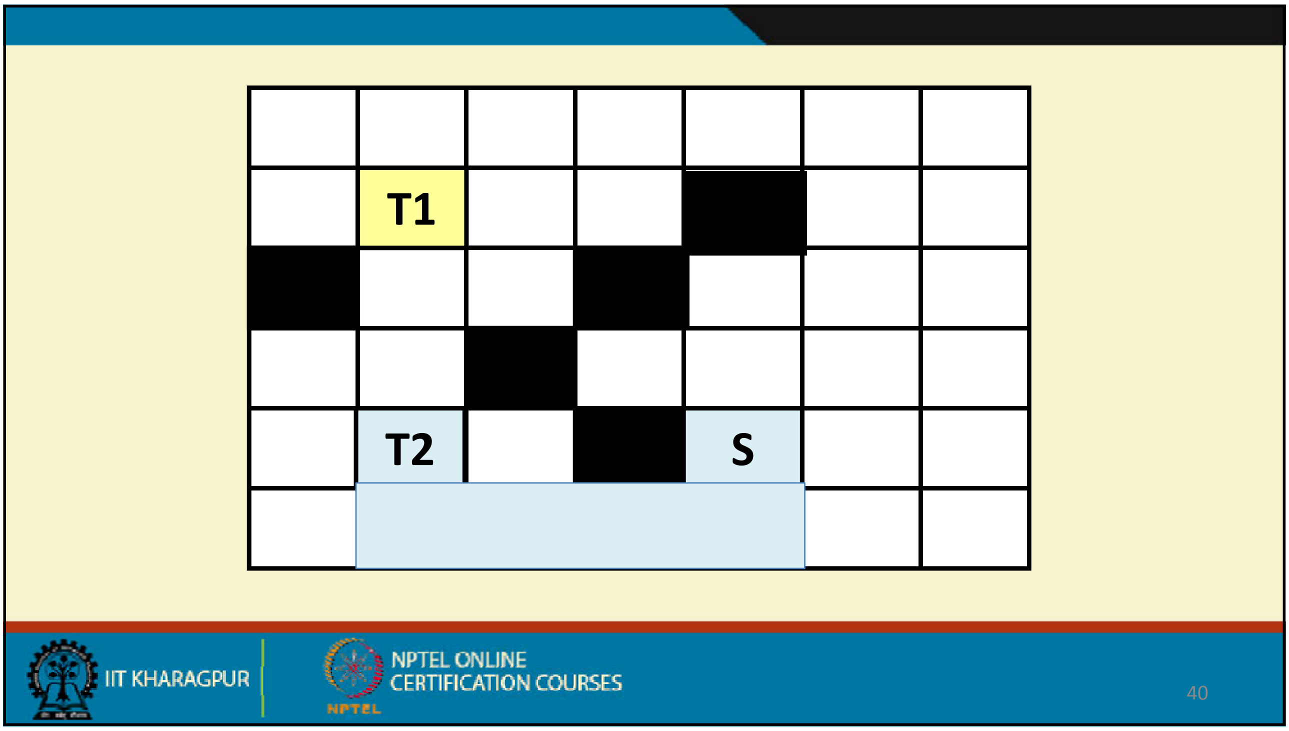
T1
T2
S
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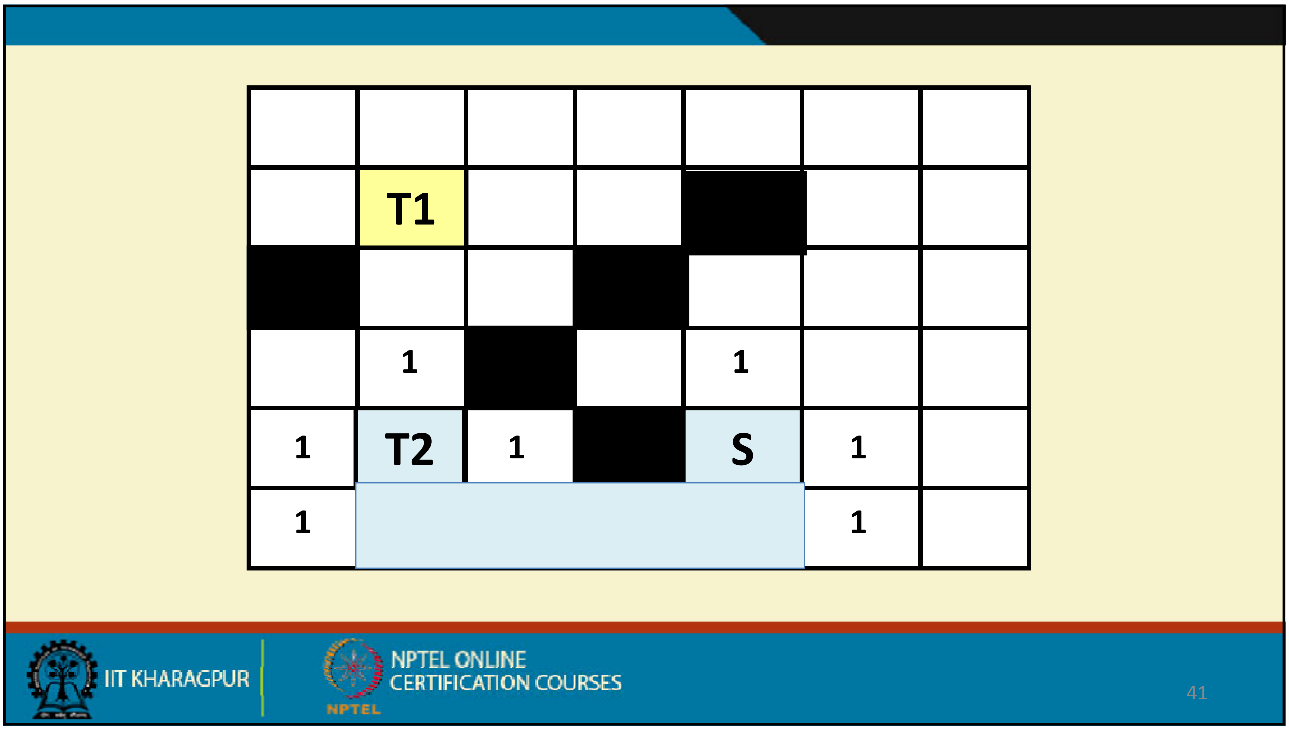
T1
1
1
1
T2
1
S
1
1
1
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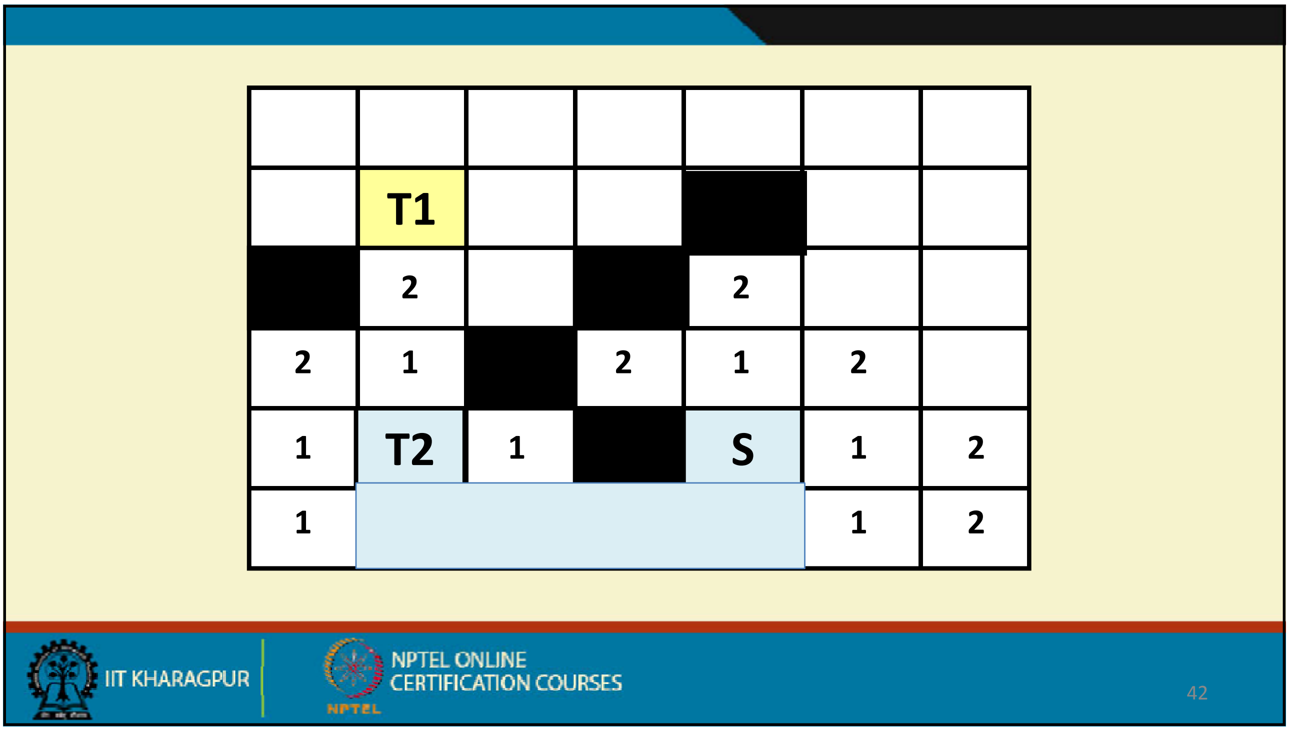
T1
2
2
2
1
2
1
2
1
T2
1
S
1
2
1
1
2
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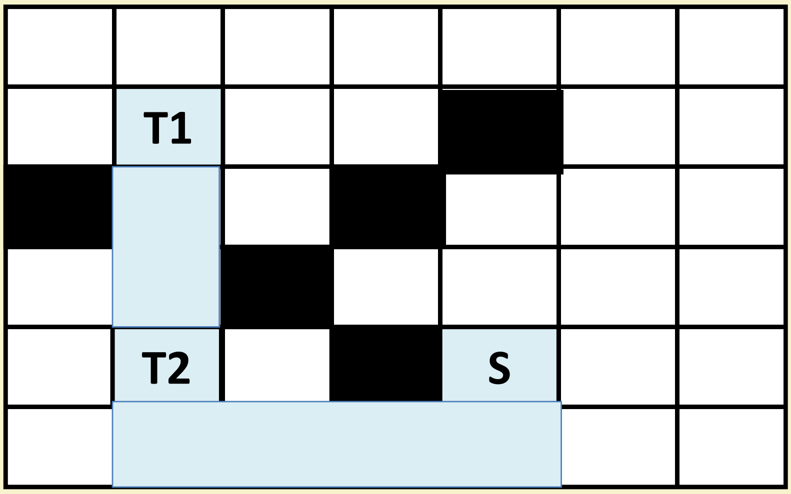


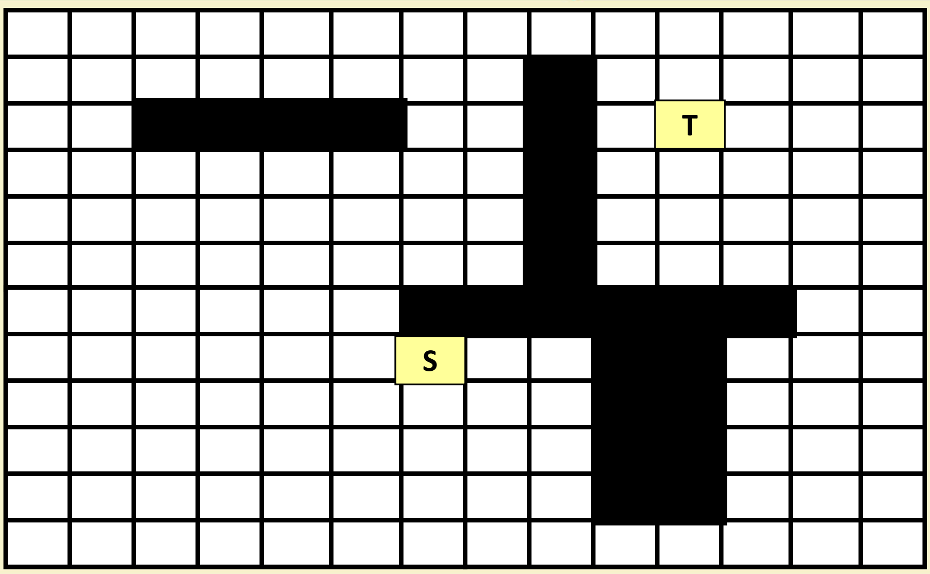
Hadlock's Algorithm

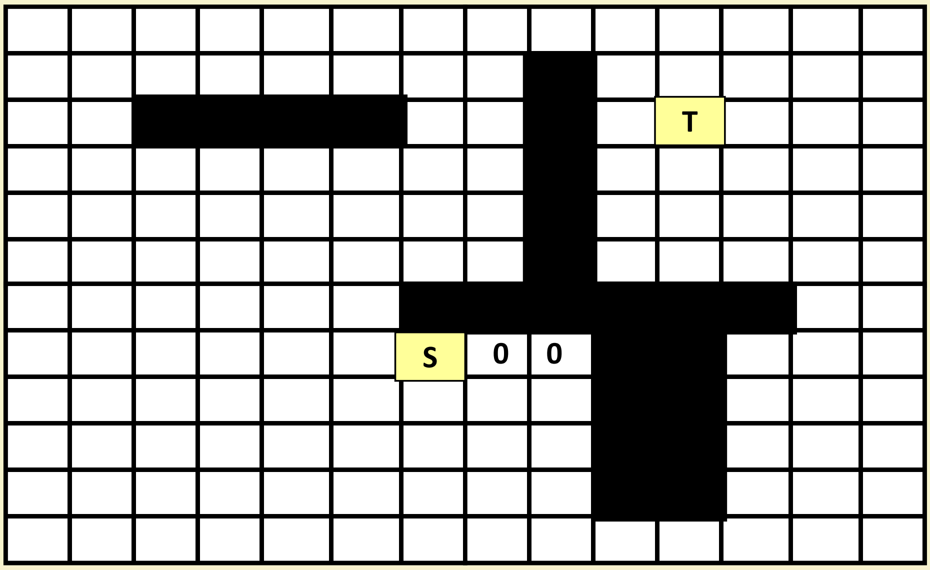
- Uses a new method for cell labeling called detour numbers.
  - A goal directed search method.
  - The detour number d(P) of a path P connecting two cells S and T is defined as the number of grid cells directed away from its target T.
  - The length of the path P is given by

    len(P) = MD (S,T) + 2 d(P)

  where MD (S,T) is the Manhattan distance between S and T.

- The cell filling phase of Lee's algorithm can be modified as follows:
  - Fill a cell with the detour number with respect to a specified target T (not by its distance from source).
  - Cells with smaller detour numbers are expanded with higher priority.
- Path retracing is of course more complex, and requires some degree of searching.





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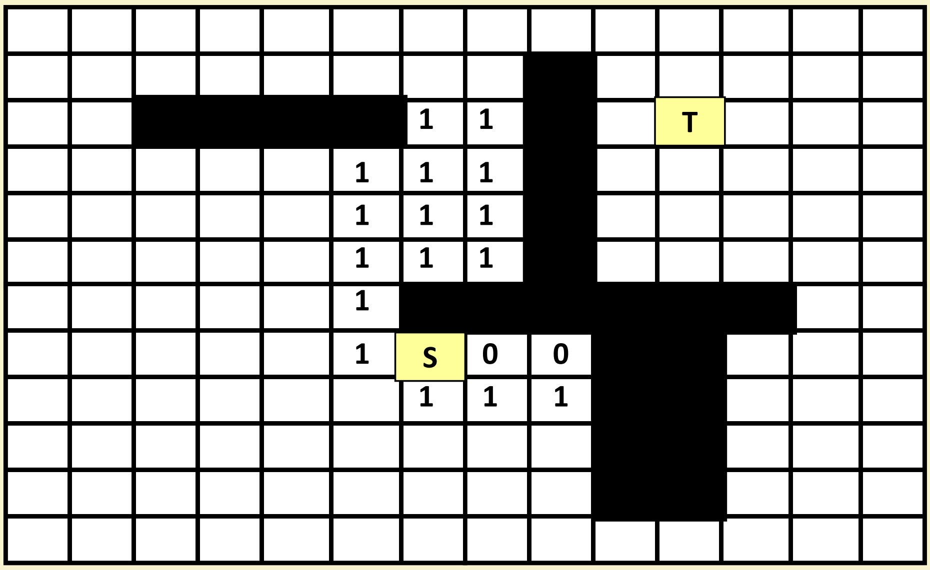

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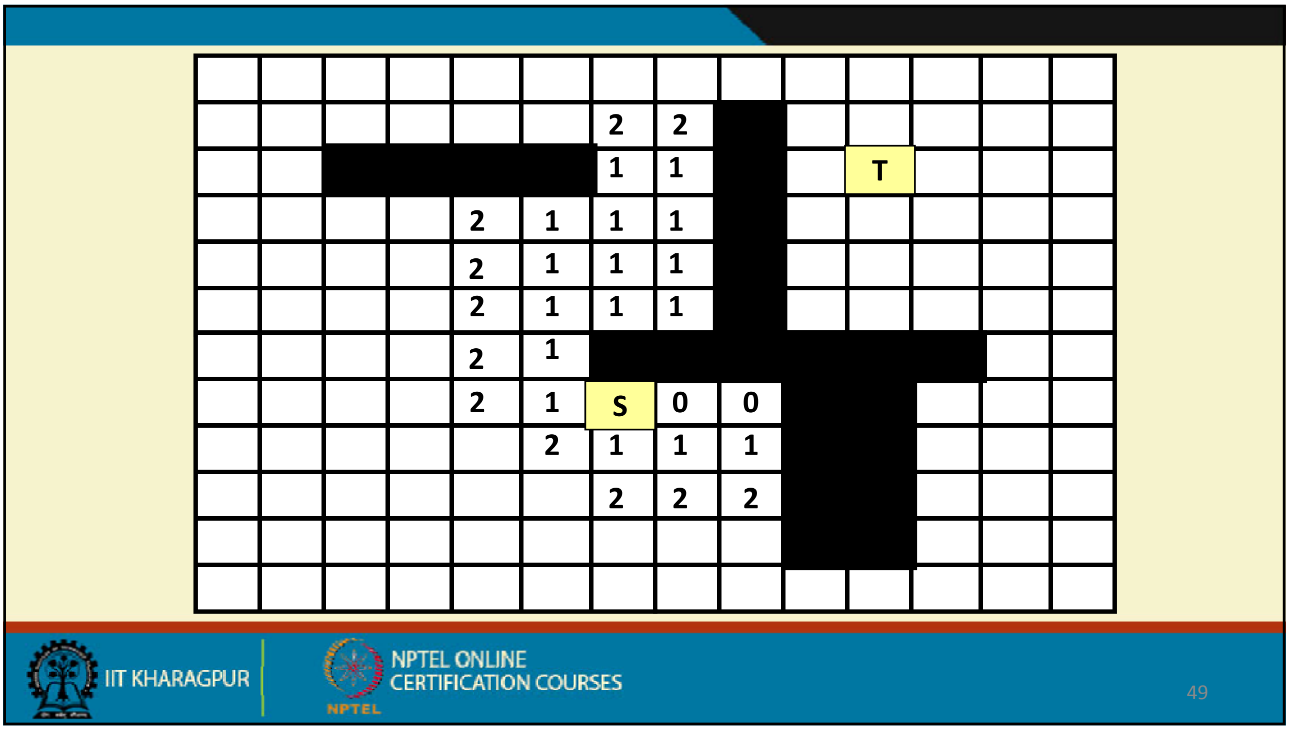
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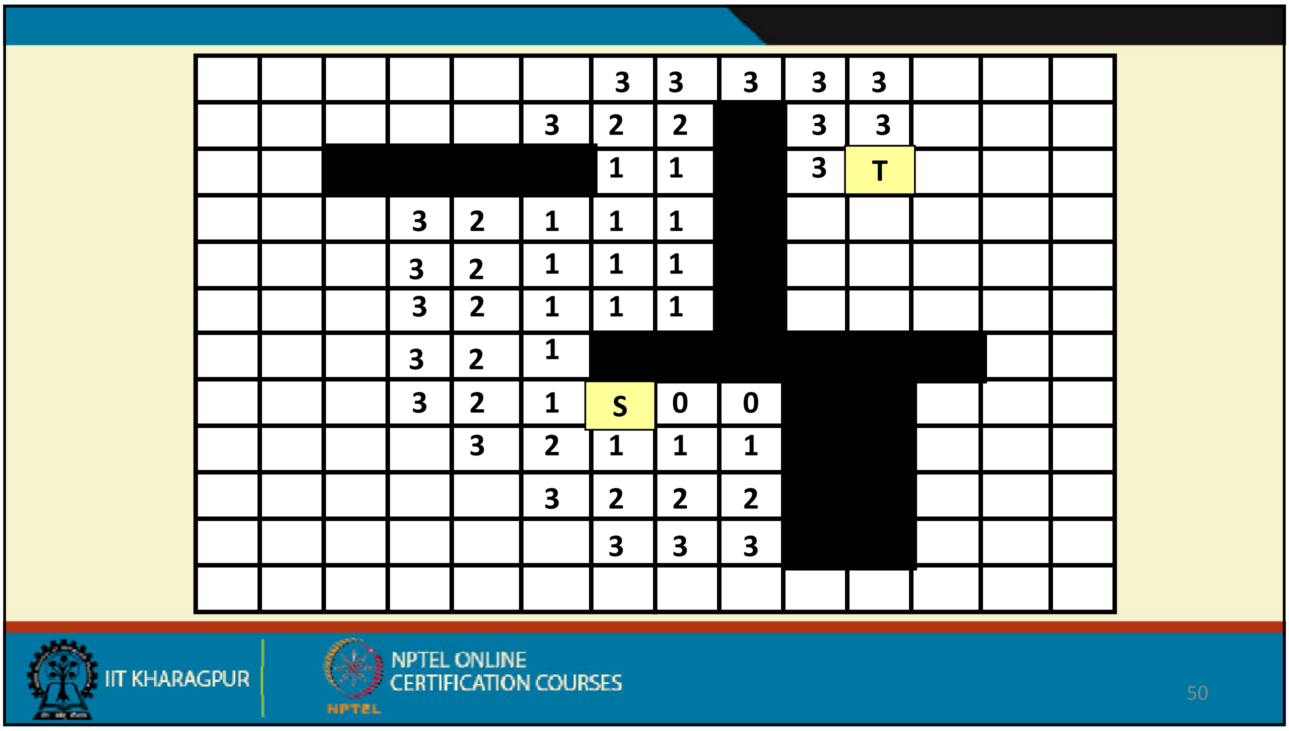
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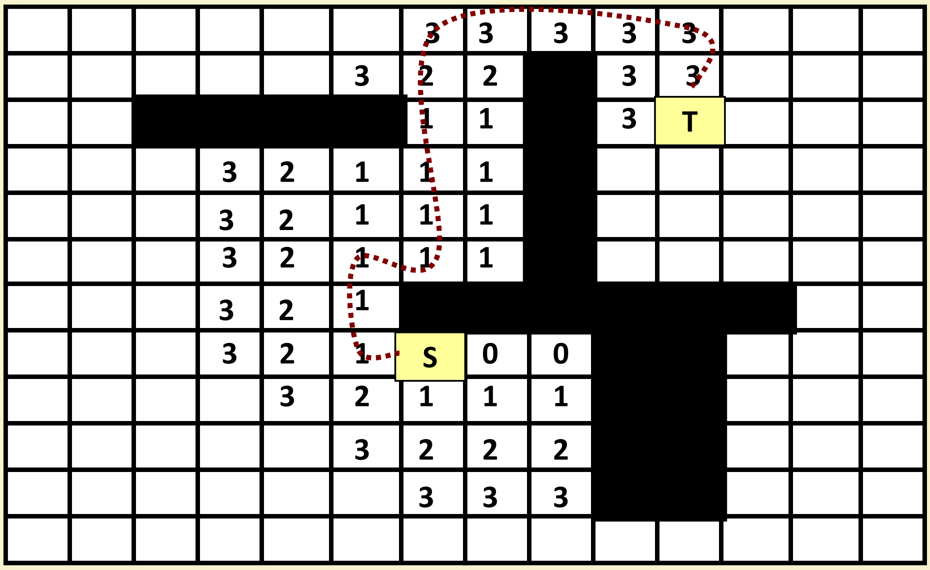


- Advantages:
  - Number of grid cells filled up is considerably less as compared to Lee's algorithm.
  - Running time for an NxN grid ranges from O(N) to $O(N^2)$.
    - Depends on the obstructions.
    - Also locations of S and T.

Line Search Algorithm

- In maze running algorithms, the time and space complexities are too high.
- An alternative approach is called line searching, which overcomes this drawback.
- Basic idea:
  - Assume no obstacles for the time being.
  - A vertical line drawn through S and a horizontal line passing though T will intersect.
    - Manhattan path between S and T.
  - In the presence of obstacles, several such lines need to be drawn.

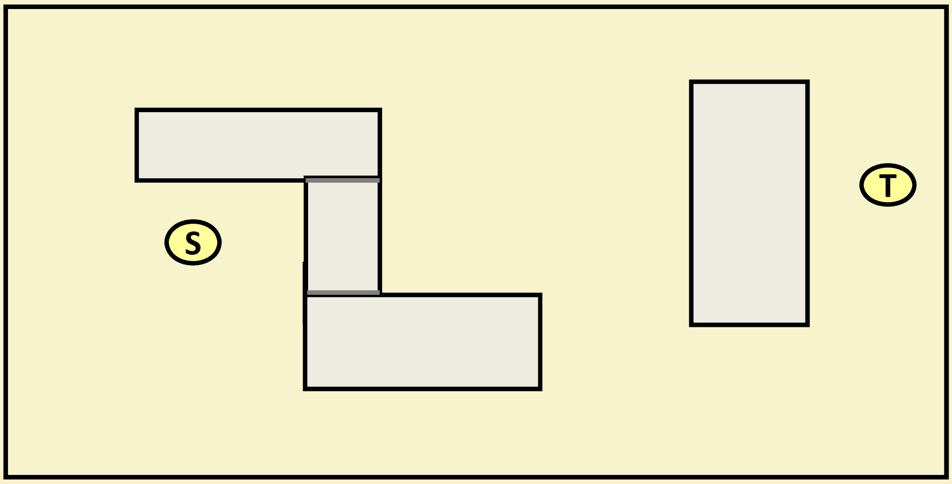
- Line search algorithms do not guarantee finding the optimal path.
  - May need several backtrackings.
  - Running time and memory requirements are significantly less.
  - Routing area and paths are represented by a set of line segments.
    - Not as a matrix as in Lee's or Hadlock's algorithm.

Mikami-Tabuchi's Algorithm

- Let S and T denote a pair of terminals to be connected.
- Step 0:
  - Generate four lines (two horizontal and two vertical) passing through S and T.
  - Extend these lines till they hit obstructions or the boundary of the layout.
  - If a line generated from S intersects a line generated from T, then a connecting path is found.
  - If they do not intersect, they are identified as trial lines of level zero.
    - Stored in temporary storage for further processing.

- Step i of Iteration: (i > 0)
  - Pick up trial lines of level i-1, one at a time.
    - Along the trial line, all its grid points are traced.
    - Starting from these grid points, new trial lines (of level i) are generated perpendicular to the trial line of level i-1.
  - If a trial line of level i intersects a trial line (of any level) from the other terminal point, the connecting path can be found.
    - By backtracing from the intersection point to S and T.
    - Otherwise, all trial lines of level i are added to temporary storage, and the procedure repeated.
- The algorithm guarantees to find a path if it exists.

Illustration

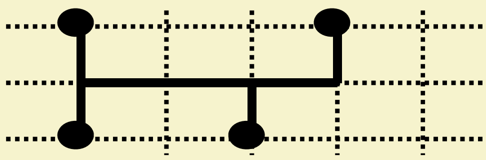


Hightower's Algorithm

- Similar to Mikami-Tabuchi's algorithm.
  - Instead of generating all line segments perpendicular to a trial line, consider only those lines that can be extended beyond the obstacle which blocked the preceding trial line.
- <u>Steps of the algorithm:</u>
  - Pass a horizontal and a vertical line through source and target points (called first-level probes).
  - If the source and the target lines meet, a path is found.
  - Otherwise, pass a perpendicular line to the previous probe whenever it intersects an obstacle.
    - Concept of *escape point* and *escape line*.

Steiner Trees

- A tree interconnecting a set $P=\{P_1,\ldots,P_n\}$ of specified points in the rectilinear plane and some arbitrary points is called a (rectilinear) Steiner tree of P.



- A Steiner tree with minimum total cost is called a Steiner minimal tree (SMT).
  – The general SMT problem is NP-hard.

Steiner Tree Based Algorithms

- Minimum length Steiner trees:
  – Goal is to minimize the sum of the length of the edges of the tree.
  – Both exact and approximate versions exist.
- Weigted Steiner trees:
  – Given a plane partitioned into a collection of weighted regions, an edge with length L in a region with weight W has cost LW.
- Steiner trees with arbitrary orientations:
  – Allows lines in non-rectilinear directions like $+45^o$ and -45^o.