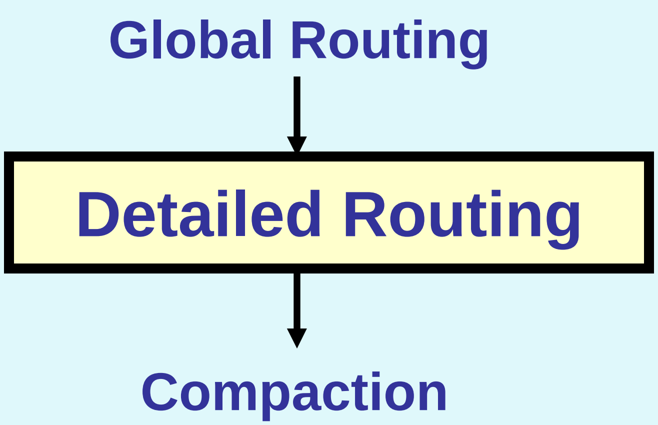
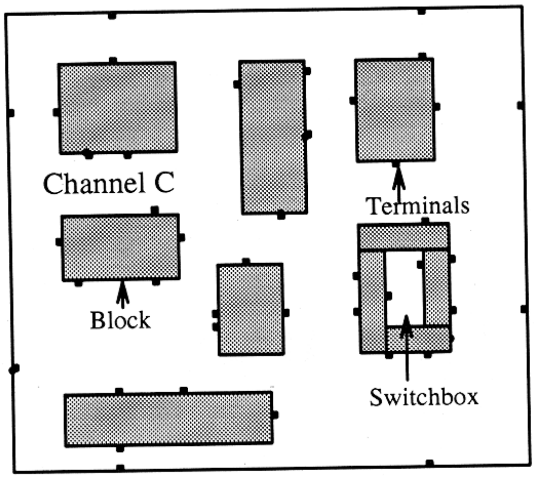
Detailed Routing

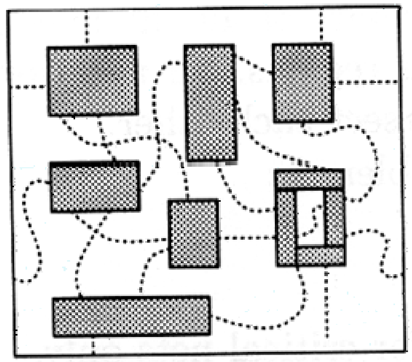
Detailed Routing

- Find actual geometric layout of each net within assigned routing regions.
- No layouts of two different nets should intersect on the same layer.
- Problem is solved incrementally, one region at a time in a predefined order.

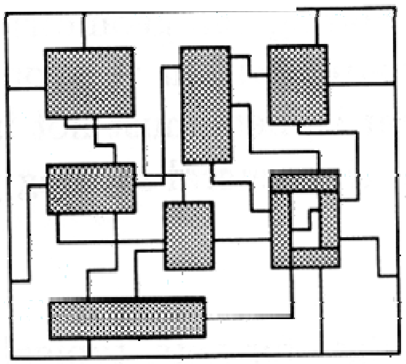


A Routing Example





Global Routing
(a)



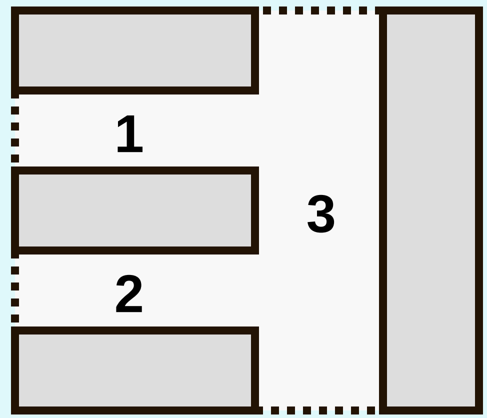
Detailed Routing
(b)

After Global Routing

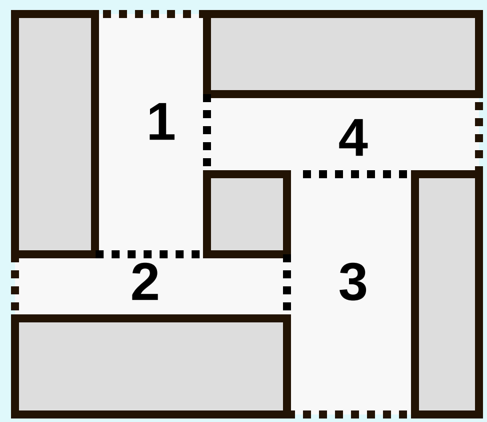
- **The two-stage routing method is a powerful technique for routing in VLSI circuits.**
- **During the global routing stage**
  - **The routing region is partitioned into a collection of rectangular regions.**
  - **To interconnect each net, a sequence of sub-regions to be used is determined.**
  - **All nets crossing a given boundary of a routing region are called *floating terminals*.**
  - **Once the sub-region is routed, these floating terminals become fixed terminals for subsequent regions.**

Order of Routing Regions

- Slicing placement topology
- Nets can be routed by considering channels 1, 2 and 3 in order.



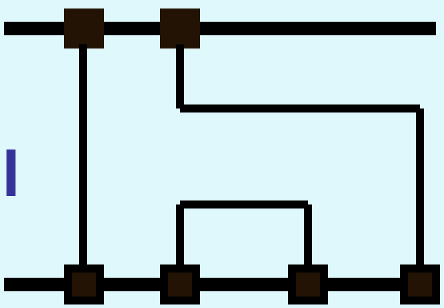
- Non-slicing placement topology.
- Channels with cyclic constraints.
- Some of the routing regions are to be considered as switchboxes.

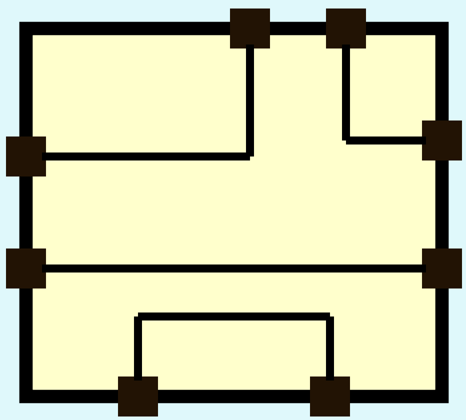


Channels and Switchboxes

- There are normally two kinds of rectilinear regions.
  - **Channels**: routing regions having two parallel rows of fixed terminals.
  - **Switchboxes**: generalizations of channels that allow fixed terminals on all four sides of the region.

Channel





Switchbox

Routing Considerations

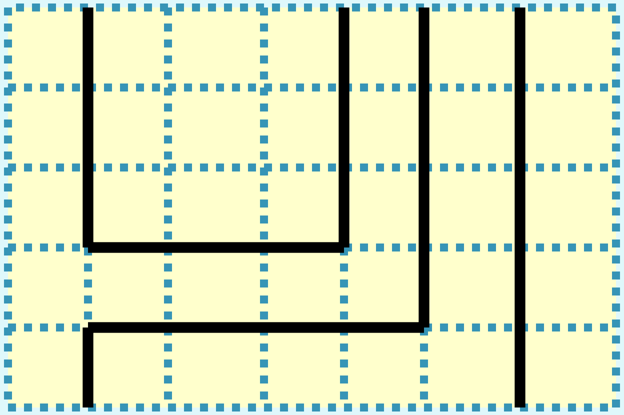
- **Number of terminals**
  - Majority of nets are two-terminal ones.
  - For some nets like clock and power, number of terminals can be very large.
  - Each multi-terminal net can be decomposed into several two-terminal nets.
- **Net width**
  - Power and ground nets have greater width.
  - Signal nets have less width.

Contd.

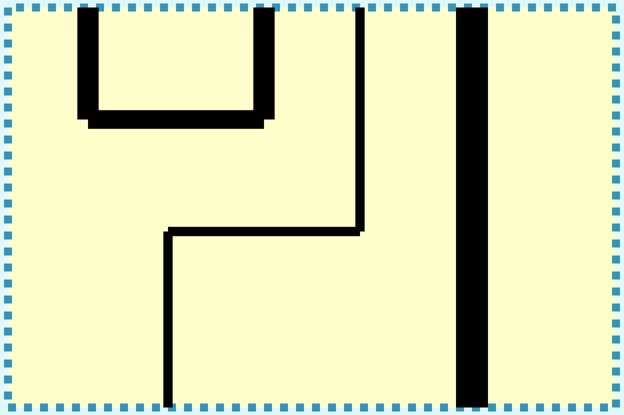
- **Via restrictions**
  - Regular: only between adjacent layers.
  - Stacked: passing through more than two layers.
- **Boundary type**
  - Regular: straight border of routing region
  - Irregular
- **Number of layers**
  - Modern fabrication technology allows at least five layers of routing.
- **Net types**
  - Critical: power, ground, clock nets
  - Non-critical: signal nets

Routing Models

- **Grid-based model**
  - A grid is super-imposed on the routing region.
  - Wires follow paths along the grid lines.



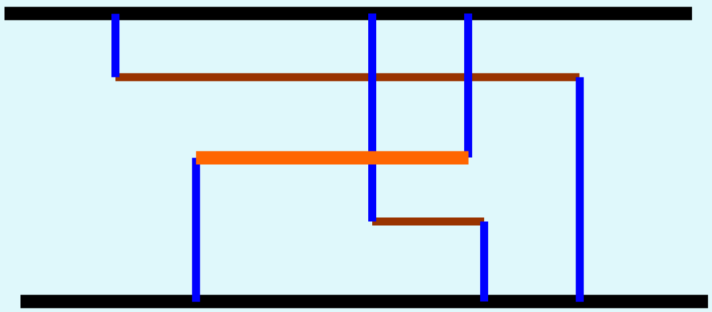
- **Gridless model**
  - Does not follow the gridded approach.



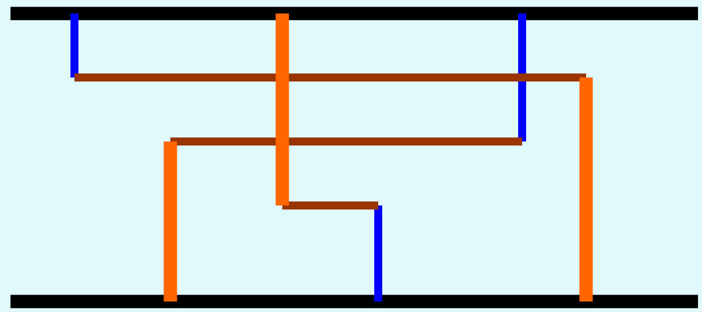
Models for Multi-Layer Routing

- **Unreserved layer model**
  - **Any net segment is allowed to be placed in any layer.**
- **Reserved layer model**
  - **Certain types of segments are restricted to particular layer(s).**
    - **Two-layer (HV, VH)**
    - **Three-layer (VHV, HVH)**

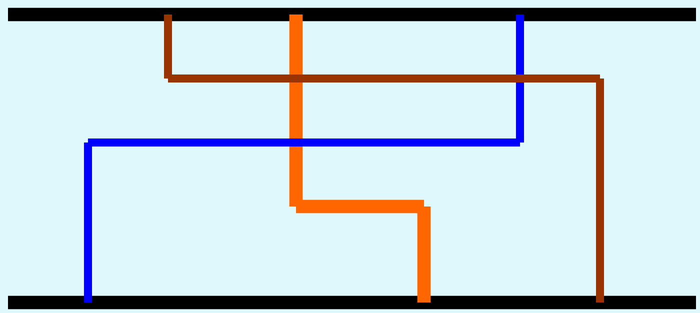
Illustration



HVH Model



VHV Model

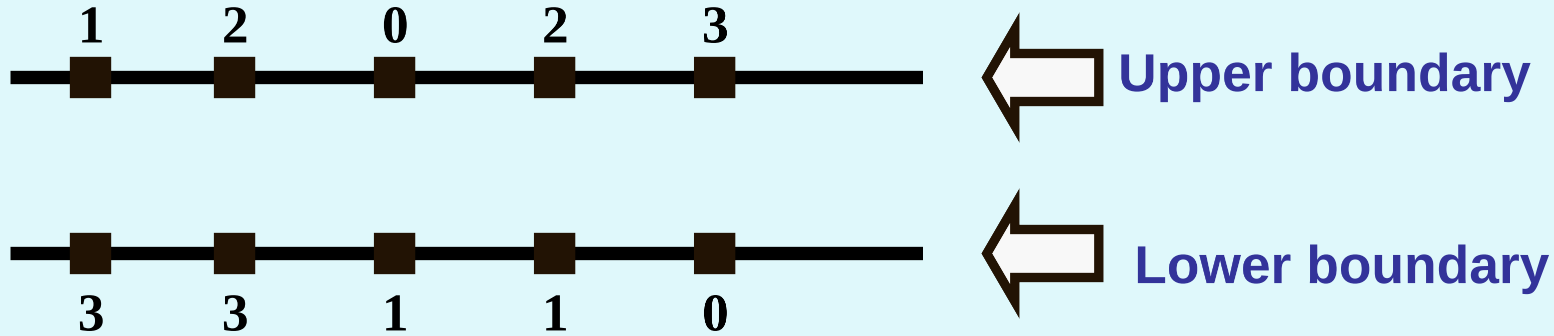


Unreserved Layer Model

Channel Routing

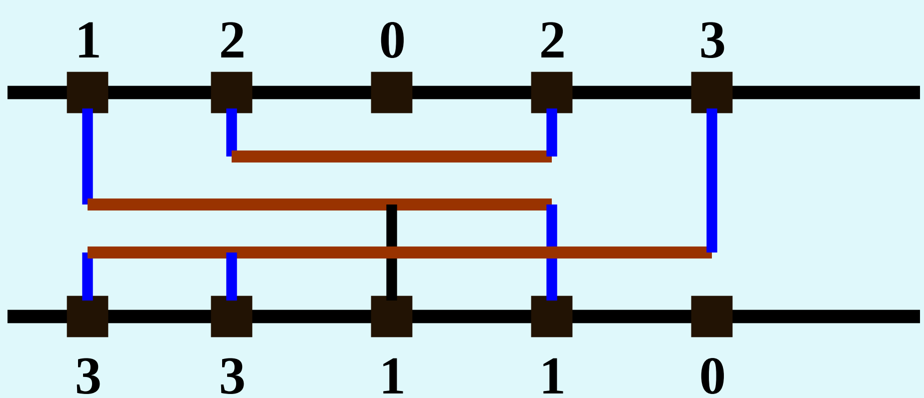
- **In channel routing, interconnections are made within a rectangular region having no obstructions.**
  - **A majority of modern-day ASIC's use channel routers.**
  - **Algorithms are efficient and simple.**
  - **Guarantees 100% completion if channel width is adjustable.**
- **Some terminologies:**
  - **Track: horizontal row available for routing.**
  - **Trunk: horizontal wire segment.**
  - **Branch: vertical wire segment connecting trunks to terminals.**
  - **Via: connection between a branch and a trunk.**

Channel Routing Problem :: Terminologies



Net list:: TOP = [1 2 0 2 3]

BOT = [3 3 1 1 0]



Problem Formulation

- The channel is defined by a rectangular region with two rows of terminals along its top and bottom sides.
  - Each terminal is assigned a number between 0 and N.
  - Terminals having the same label i belong to the same net i.
  - A ‘0’ indicates no connection.
- The netlist is usually represented by two vectors TOP and BOT.
  - TOP(k) and BOT(k) represents the labels on the grid points on the top and bottom sides of the channel in column k, respectively.

Contd.

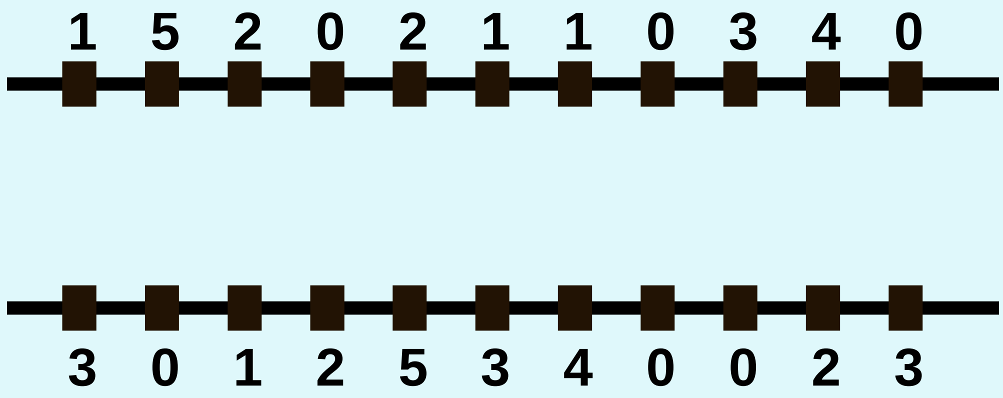
- The task of the channel router is to:
  - Assign horizontal segments of nets to tracks.
  - Assign vertical segments to connect
    - Horizontal segments of the same net in different tracks.
    - The terminals of the net to horizontal segments of the net.
- Channel height should be minimized.
- Horizontal and vertical constraints must not be violated.

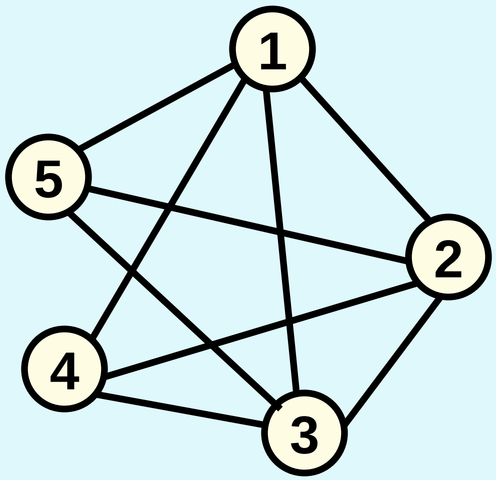
Contd.

- **Horizontal constraints between two nets:**
  - The horizontal span of two nets overlaps each other.
  - The nets must be assigned to separate tracks.
- **Vertical constraints between two nets:**
  - There exists a column such that the terminal i on top of the column belongs to one net, and the terminal j on bottom of the column belongs to the other net.
  - Net i must be assigned a track above that for net j.

Horizontal Constraint Graph (HCG)

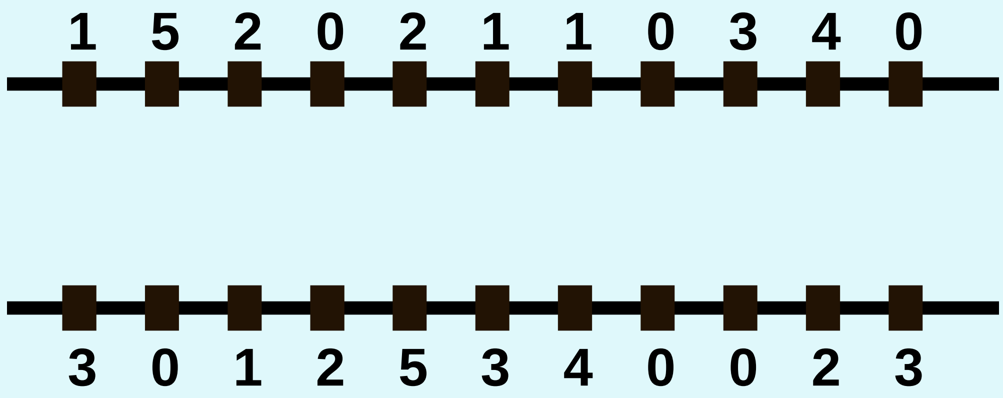
- It is a graph where vertices represent nets, and edges represent horizontal constraints.

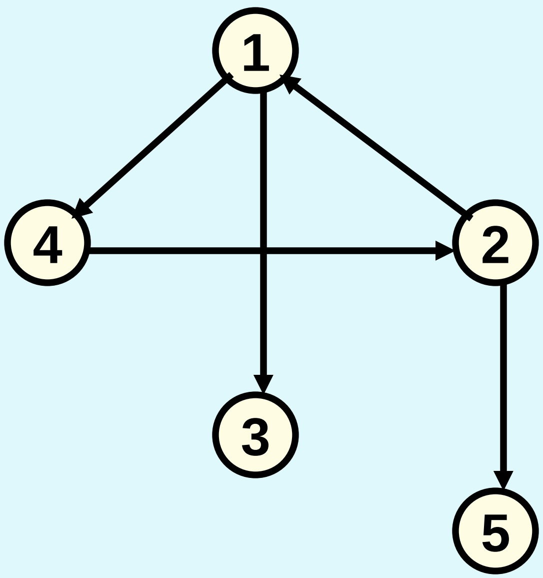




Vertical Constraint Graph (VCG)

- It is a directed graph where vertices represent nets, and edges represent vertical constraints.





Two-layer Channel Routing

- Left-Edge Algorithms (LEA)
  - Basic Left-Edge Algorithm
  - Left-Edge Algorithm with Vertical Constraints
  - Dogleg Router
- Constraint-Graph Based Algorithm
  - Net Merge Channel Router
  - Gridless Channel Router
- Greedy Channel Router
- Hierarchical Channel Router

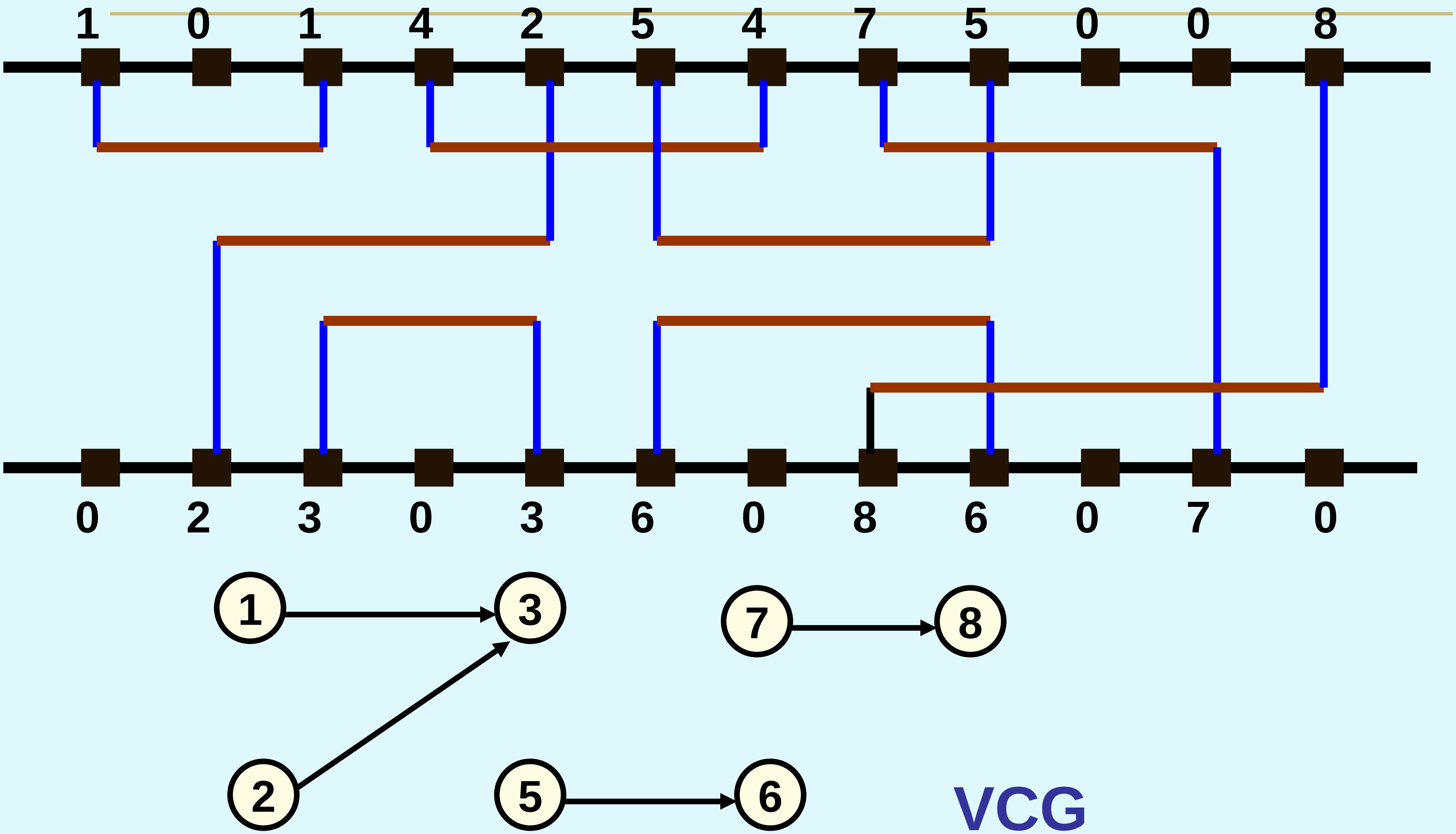
Basic Left Edge Algorithm

- **Assumptions:**
  - Only two-terminal nets.
  - No vertical constraints.
  - HV layer model.
  - Doglegs are not allowed.
- **Basic Steps:**
  - Sort the nets according to the x-coordinate of the leftmost terminal of the net.
  - Route the nets one-by-one according to the order.
  - For a net, scan the tracks from top to bottom, and assign it to the first track that can accommodate it.
- **In the absence of vertical constraints, the algorithm produces a minimum-track solution.**

Contd.

- **Extension to Left-Edge Algorithm**
  - Vertical constraints may exist, but there are no directed cycles in the VCG.
  - Select a net for routing if
    - The x-coordinate of the leftmost terminal is the least.
    - There is no edge incident on the vertex corresponding to that net in the VCG.
  - After routing a net, the corresponding vertex and the incident edges are deleted from the VCG.
  - Other considerations same as the basic left-edge algorithm.

Illustration



VCG

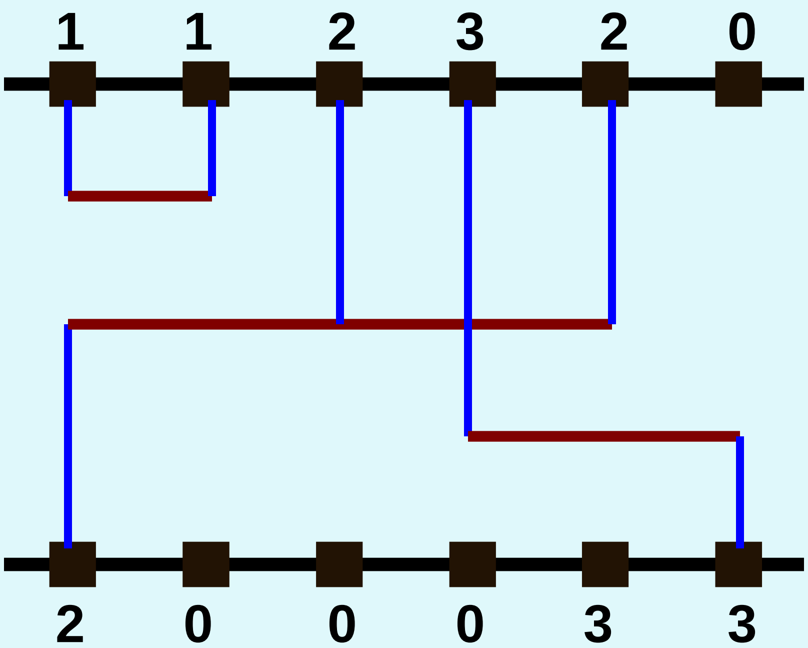
Dogleg Router

- <u>Drawback of LEA</u>
  - The entire net is on a single track.
  - Sometimes leads to routing with more tracks than necessary.
- Doglegs are used to place parts of the same net on different tracks.
  - A dogleg is a vertical segment that connects two trunks located in two different tracks.
  - May lead to a reduction in channel height.

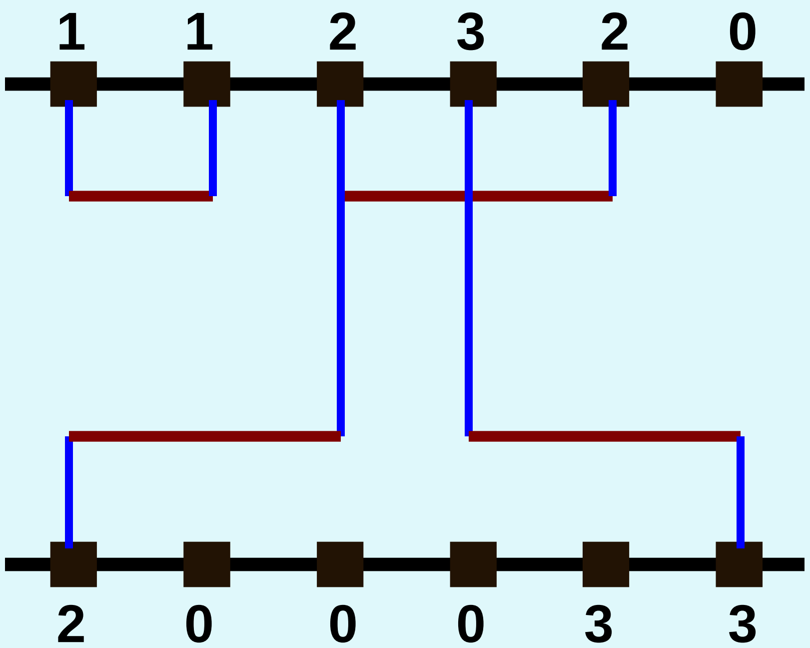
Contd.

- Dogleg router allows multi-terminal nets and vertical constraints.
  - Multi-terminal nets can be broken into a series of two-terminal nets.
- Cannot handle cyclic vertical constraints.

Example



No dogleg
3 tracks

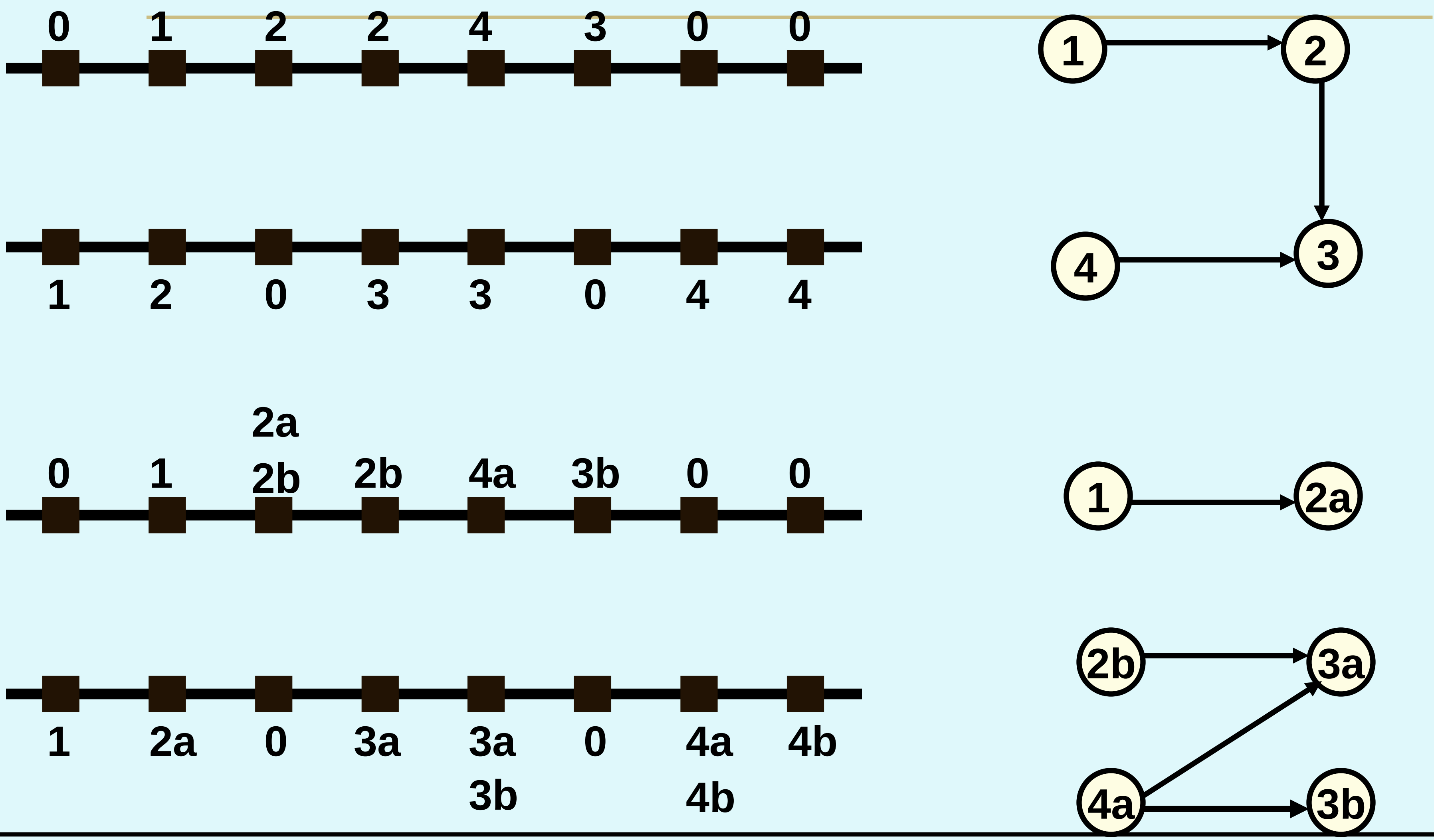


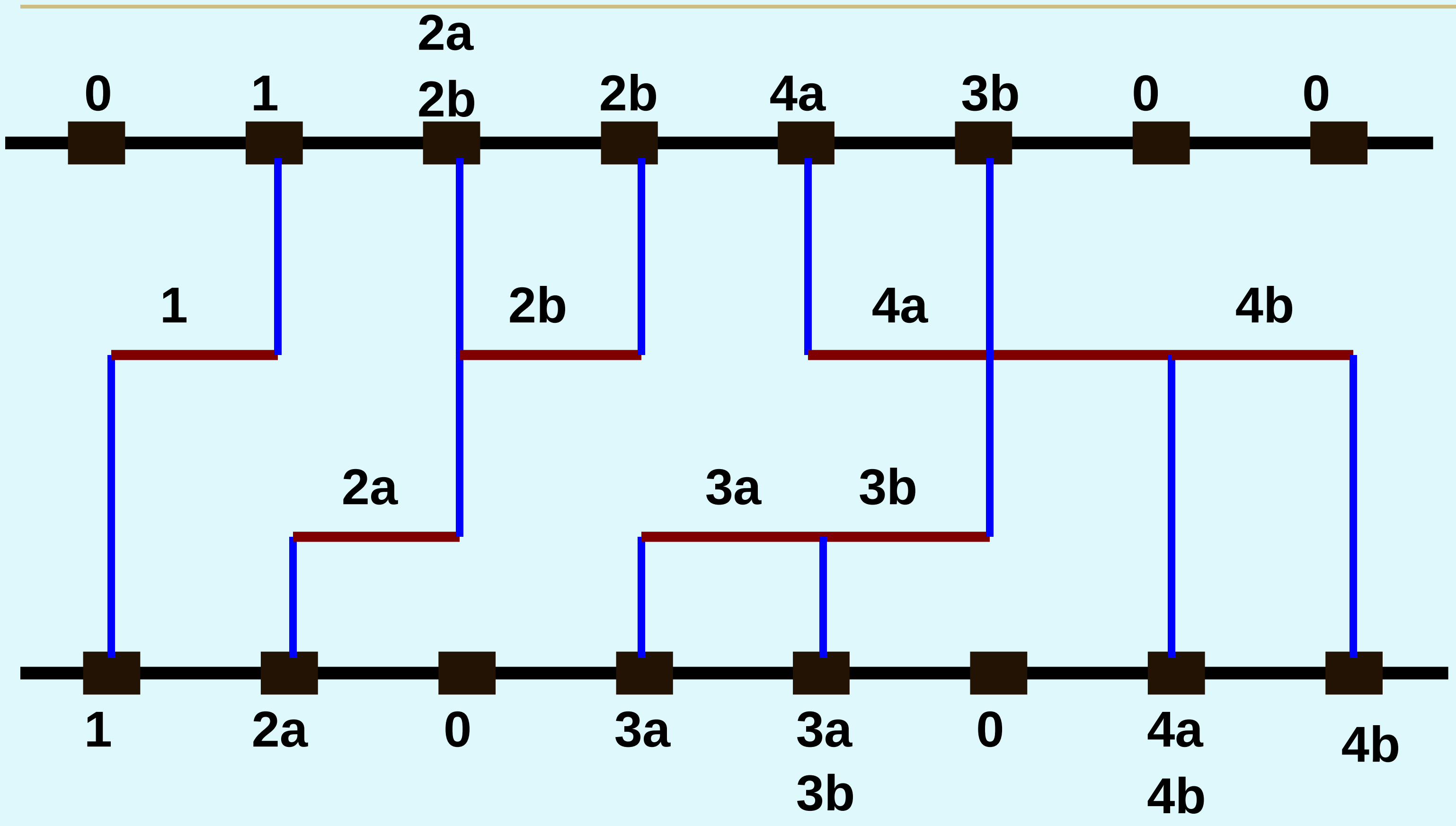
With dogleg
2 tracks

Dogleg Router: Algorithm

- **Step 1:**
  - If cycle exists in the VCG, return with failure.
- **Step 2:**
  - Split each multi-terminal net into a sequence of 2-terminal nets.
    - A net 2 .. 2 .. 2 will get broken as 2a .. 2a 2b .. 2b.
  - HCG and VCG gets modified accordingly.
- **Step 3:**
  - Apply the extended left-edge algorithm to the modified problem.

Illustration



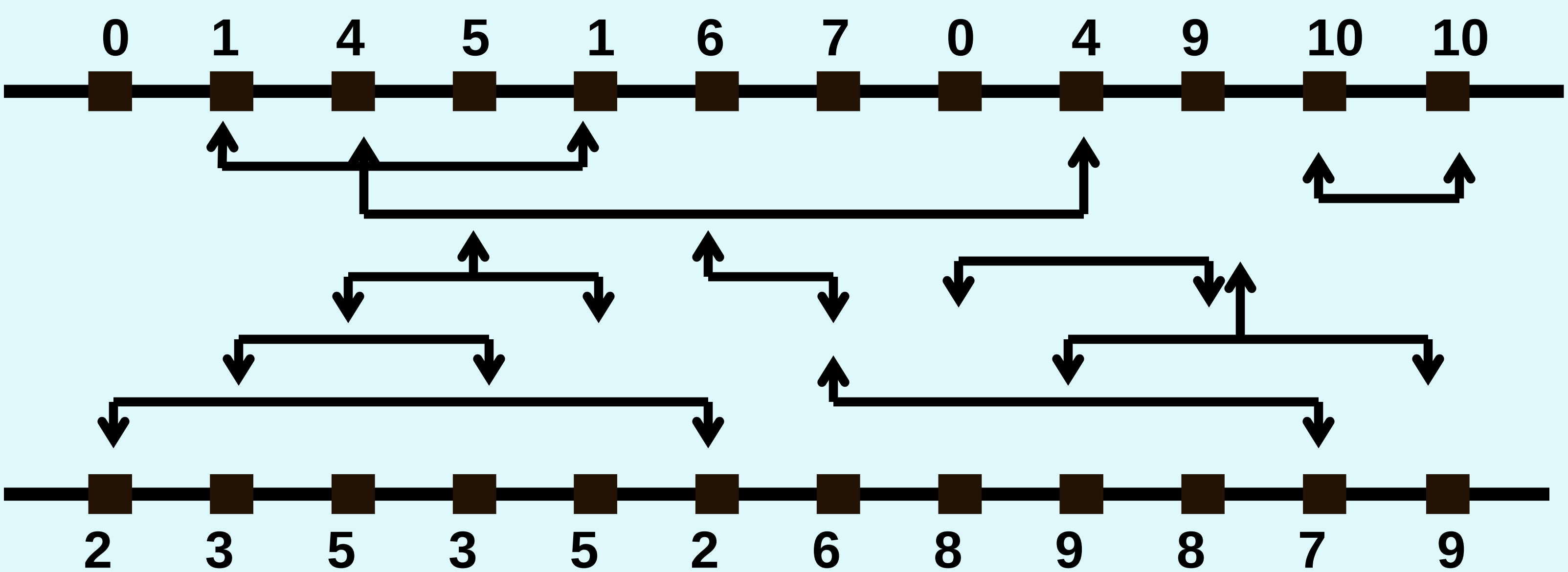

2a
2b
0
1
2b
4a
3b
0
0
1
2b
4a
4b
2a
3a
3b
1
2a
0
3a
3a
3b
0
4a
4b
4b

Net Merge Channel Router

- Due to Yoshimura and Kuh.
- Basic idea:
  - If there is a path of length *p* in the VCG, at least *p* horizontal tracks are required to route the channel.
  - Try to minimize the longest path in the VCG.
  - Merge nodes of VCG to achieve this goal.
- Does not allow doglegs or cycles in the VCG.
- How does it work?
  - Partition the routing channel into a number of regions called “zones”.
  - Nets from adjacent zones are merged.
    - Merged nets are treated as a “composite net” and assigned to a single track.

Contd.

- **Key steps of the algorithm:**
  - a) Zone representation
  - b) Net merging
  - c) Track assignment
- **An example:**



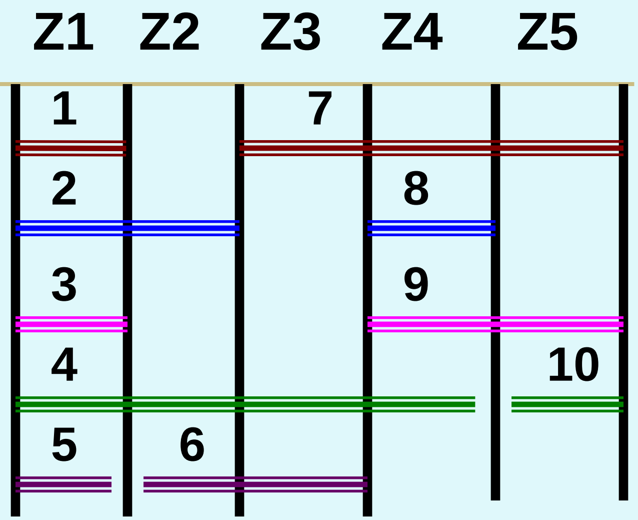
Step 1: Zone Representation

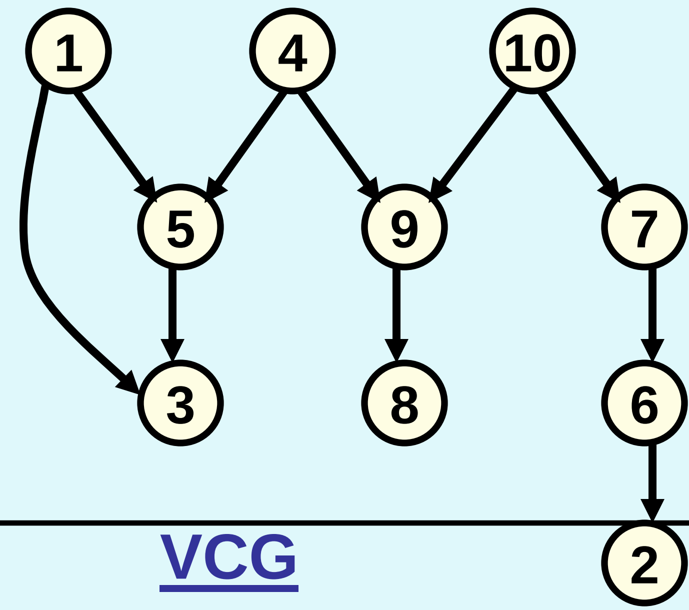
- Let *S(i)* denote the set of nets whose horizontal segments intersect column *i*.
- Take only those *S(i)* which are maximal, that is, not a proper subset of some other *S(j).*
- Define a zone for each of the maximal sets.
- In terms of HCG / interval graph, a zone corresponds to a maximal clique in the graph.

Zone Table

Column	S(i)	Zone
1	{2}	
2	{1,2,3}	
3	{1,2,3,4,5}	1
4	{1,2,3,4,5}	
5	{1,2,4,5}	
6	{2,4,6}	2
7	{4,6,7}	3
8	{4,7,8}	
9	{4,7,8,9}	4
10	{7,8,9}	
11	{7,9,10}	5
12	{9,10}	

Zone Representation





VCG

Step 2: Net Merging

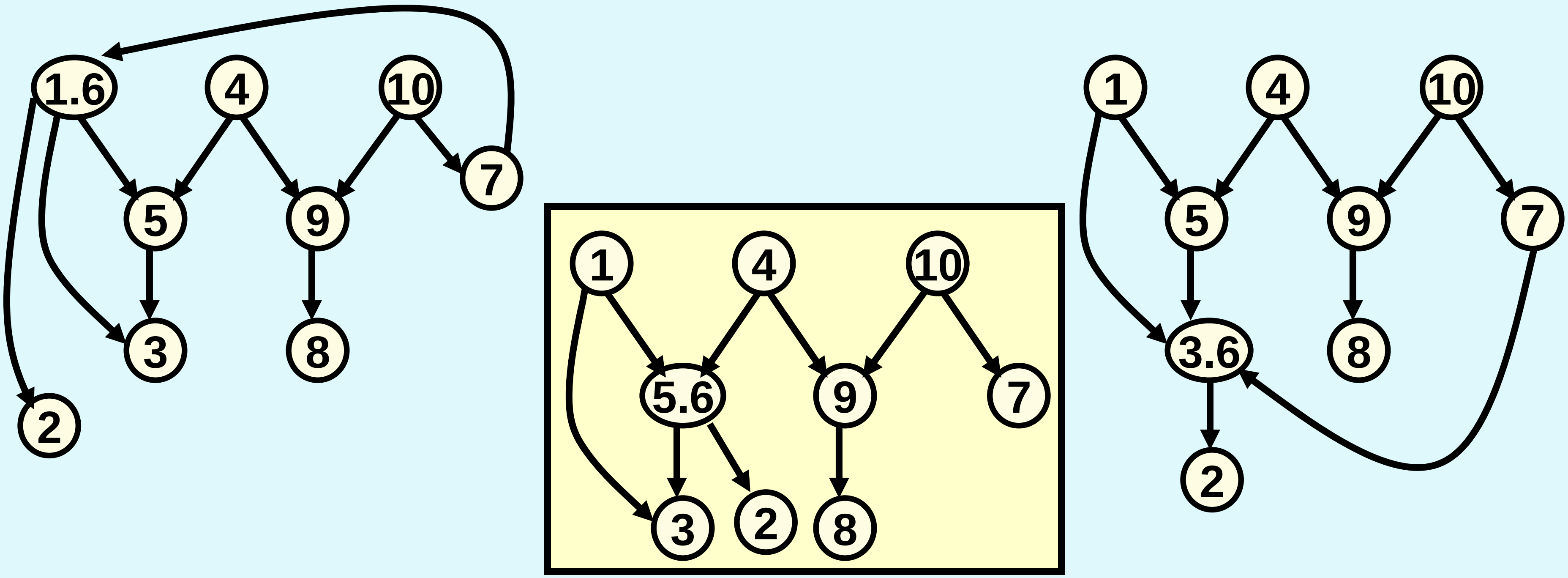
- Let N_i and N_j be two nets for which the following conditions are satisfied:
  - There is no edge between v_i and v_j in HCG.
  - There is no directed path between v_i and v_j in VCG.
- Nets N_i and N_j can then be *merged* to form a new composite net.
  - Modifies VCG by merging nodes v_i and v_j into a single node $v_{i.j}$.
  - Modifies HCG / zone representation by replacing nodes v_i and v_j by a net v_{i-j}, which occupies the consecutive zones including those of nets N_i and N_j.

Contd.

- The process is iterative:
  - Pairs of nodes are successively merged.
  - At every step of the iteration, in case of multiple choices, merge the net-pair that minimizes the length of the longest path in the VCG.
  - That is, the increase in length is minimum.
- A result:
  - If the original VCG has no cycles, then the updated VCG with merged nodes will not have cycles either.

Contd.

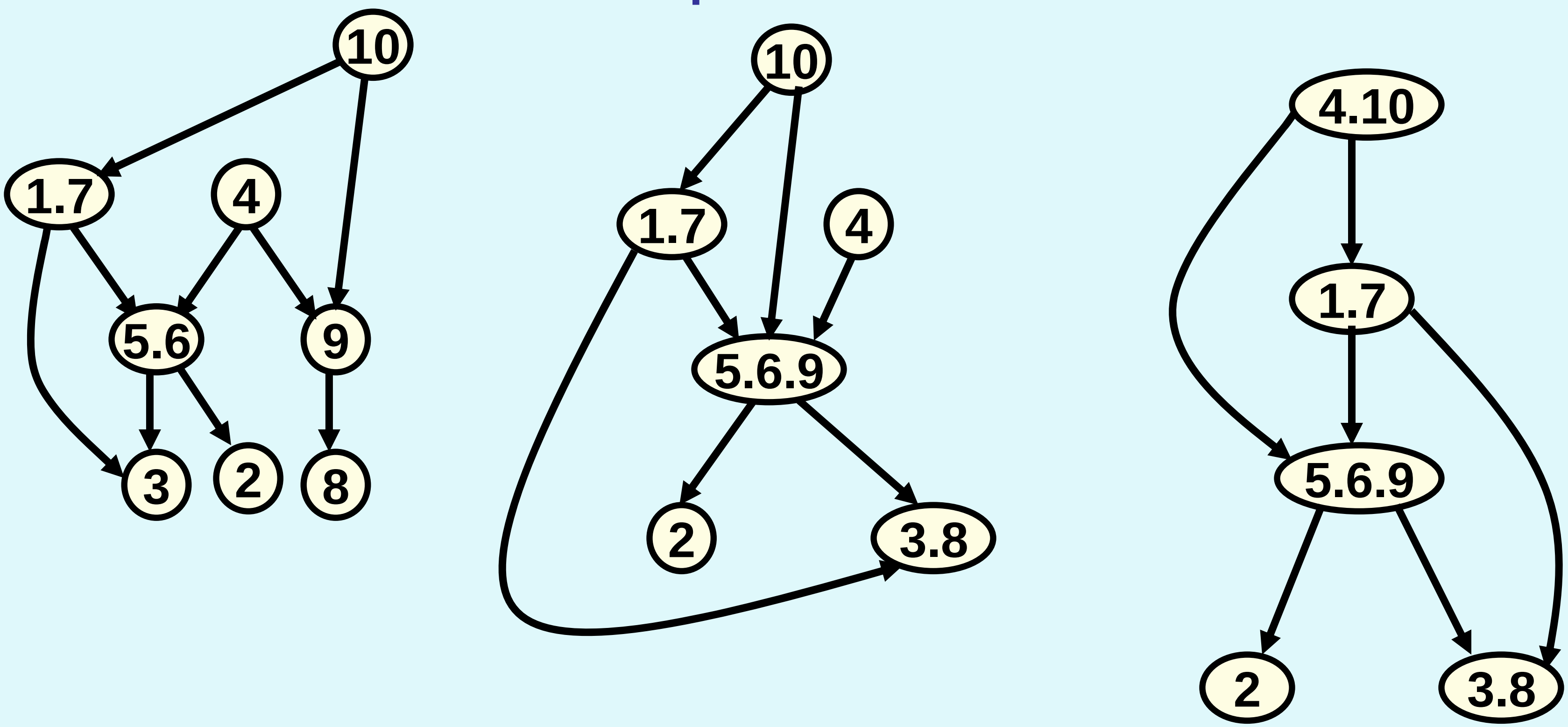
- **Iteration 1 of the example:**
  - **We can merge nets pairs (1,6), (3,6) or (5,6).**



Best Choice

Contd.

- Successive iteration steps:



Step 3: Track Assignment

- Each node in the final graph is assigned a separate track.
- Actually we apply the left-edge algorithm to assign horizontal tracks to the merged nets.
  - The list of nets sorted on their left edges, subject to the vertical constraint, is:

    [4-10, 1-7, 5-6-9, 2, 3-8]

Track 1: Nets 4 and 10

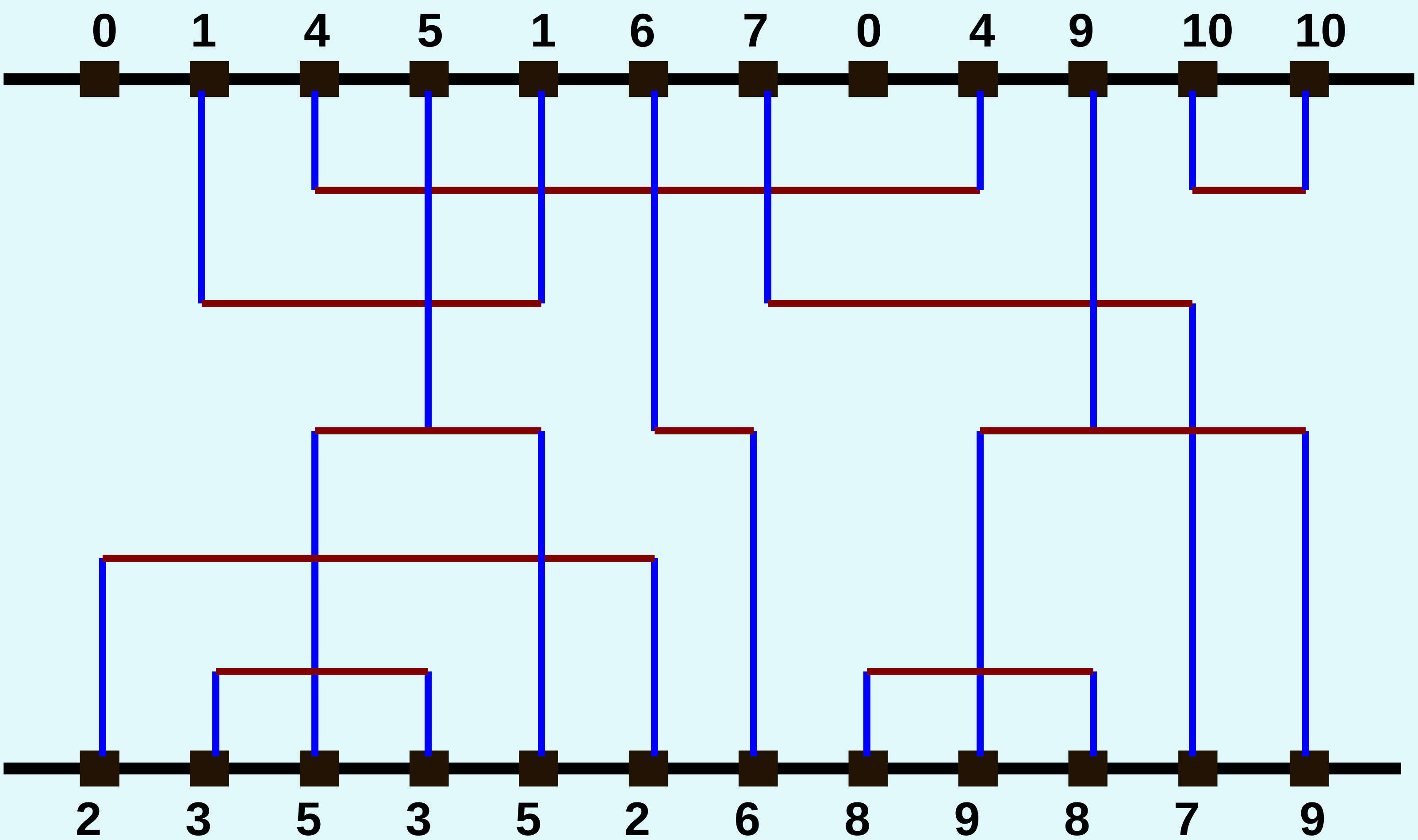
Track 2: Nets 1 and 7

Track 3: Nets 5, 6 and 9

Track 4: Net 2

Track 5: Nets 3 and 8

The Final Solution



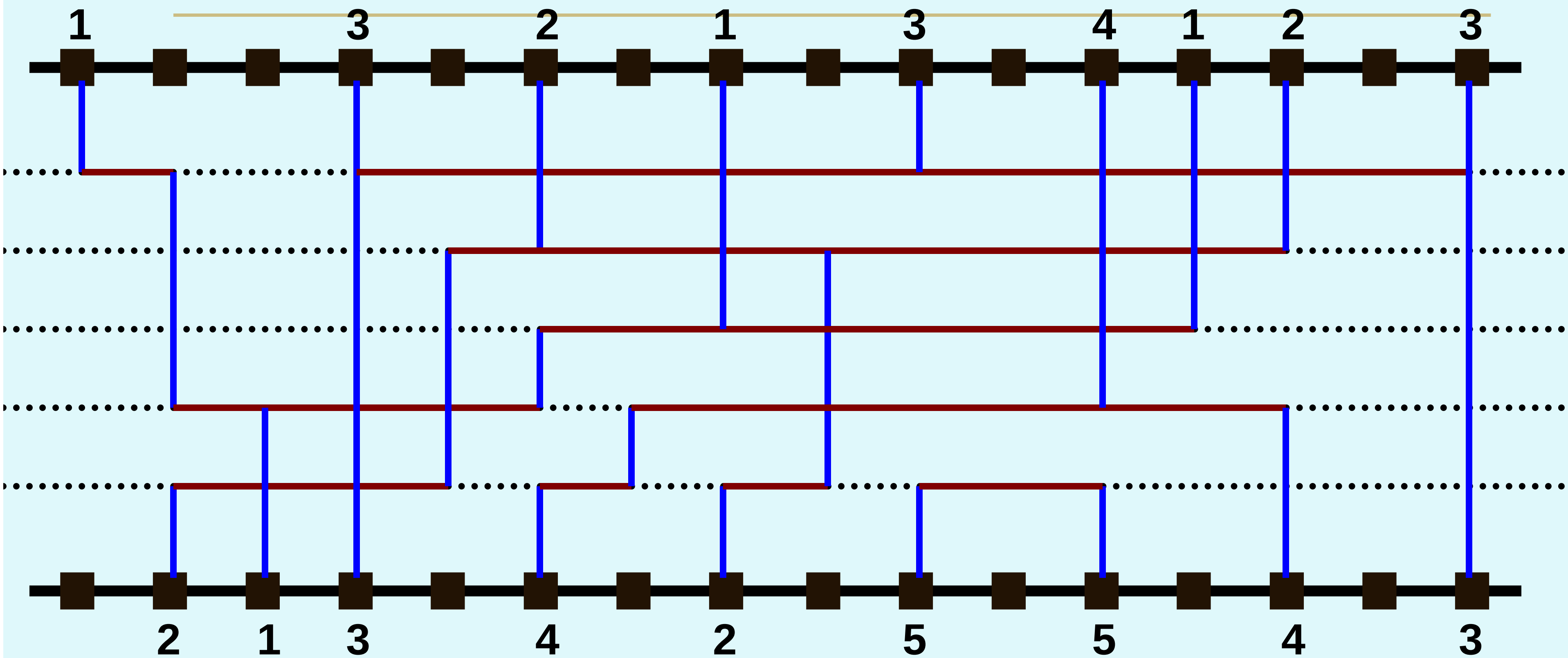
Greedy Channel Router

- The routing algorithms discussed so far route the channel one net at a time.
  - Based on left-edge algorithm or some of its variation.
- The Greedy Channel Router algorithm routes the channel column by column starting from the left.
  - Apply a sequence of greedy but intelligent heuristic at each column.
  - Objective is to maximize the number of tracks available in the next column.
- Can handle problems with cycles in VCG.
  - May need additional columns at the end of the channel.

Contd.

- **Some of the heuristics used:**
  - Place all segments column by column, starting from the leftmost column.
  - Connect any terminal to the trunk segment of the corresponding net.
  - Collapse any split net using a vertical segment.
  - Try to reduce the distance between two tracks of same net.
  - Try to move the nets closer to the boundary which contains the next terminal of that net.
  - Add additional tracks if needed.

Channel Routed using a Greedy Router



Hierarchical Channel Router

- Uses a divide-and-conquer approach.
  - A routing problem in $m \times n$ grid is reduced to $2 \times n$ grid.
  - Each column in these sub-grids is treated as a *supercell*.
  - Capacity of each vertical boundary is the sum of corresponding boundary capacities.
  - Nets are routed one at a time in the $2 \times n$ grid.
  - Each row of $2 \times n$ is partitioned into $2 \times n$ grid.
  - Terminal position for the new $2 \times n$ grids are defined by the routing in the previous hierarchy.

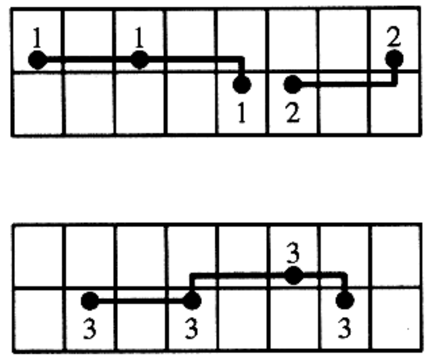
Example

1	0	1	0	0	3	0	2
0	3	0	3	1	2	3	0

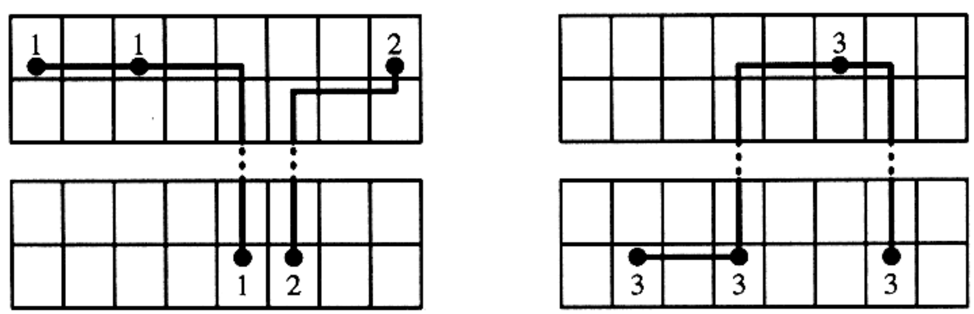
1	0	1	0	0	3	0	2
0	3	0	3	1	2	3	0

Reducing (m×n) grid to (2×n) grid

Example (contd.)



First level of hierarchy



Second level of hierarchy

Comparison of Two-Layer Channel Routers

	LEA	Dogleg	Net Merge	Greedy	Hierarchical
Model	Grid-based	Grid-based	Grid-based	Grid-based	Grid-based
Dogleg	No	Yes	Yes	Yes	Yes
Vertical constraint	No / Yes	Yes	Yes	Yes	Yes
Cyclic constraint	No	No	No	Yes	Yes

Three-Layer Channel Routing Algorithms

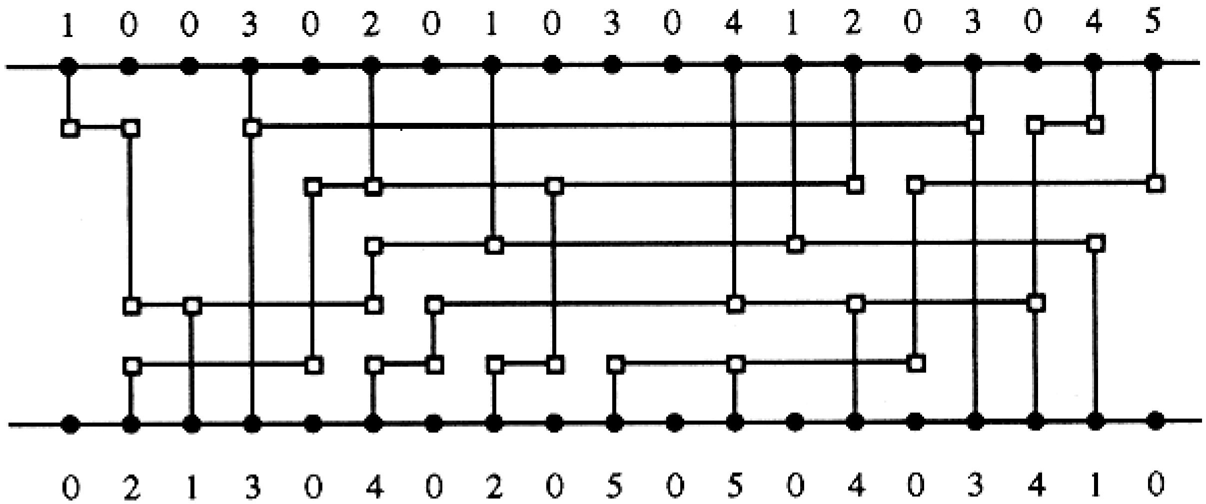
- **Several approaches:**
  - Extended Net Merge Channel Router
  - HVH Routing from HV Solution
  - Hybrid HVH-VHV Router

HVH Routing from HV Solution

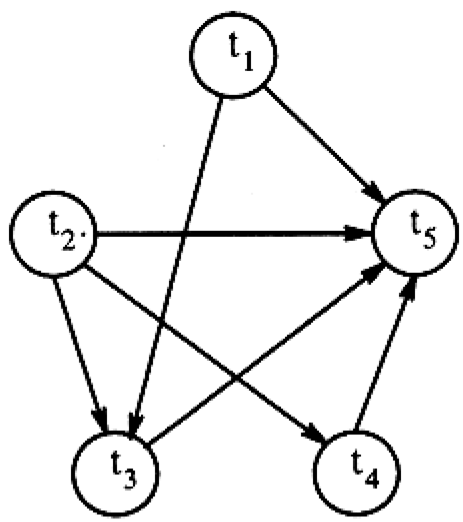
- **Very similar to the Y-K algorithm.**
  - **Systematically transform a two-layer routing solution into a three-layer routing solution.**
  - **In Y-K algorithm, nets are merged so that all merged nets forming a composite net are assigned to one track.**
  - **Here, the composite nets are merged together to form super-composite nets.**
- **Objective:**
  - **Reduce the number of super-composite nets.**

Contd.

- Two composite nets in a super-composite net can be assigned to different layers on the same track.
- A track-ordering graph is used to find the optimal pair of composite nets to be merged.
  - Vertices represent the composite (tracks) in a given two-layer solution.
  - The directed edges represent the ordering restrictions on pairs of tracks.
    - Composite interval t_i must be routed above composite interval t_j, if there exists a net $N_p \in t_i$ and $N_q \in t_j$, such that N_p and N_q have a vertical constraint.



(a)



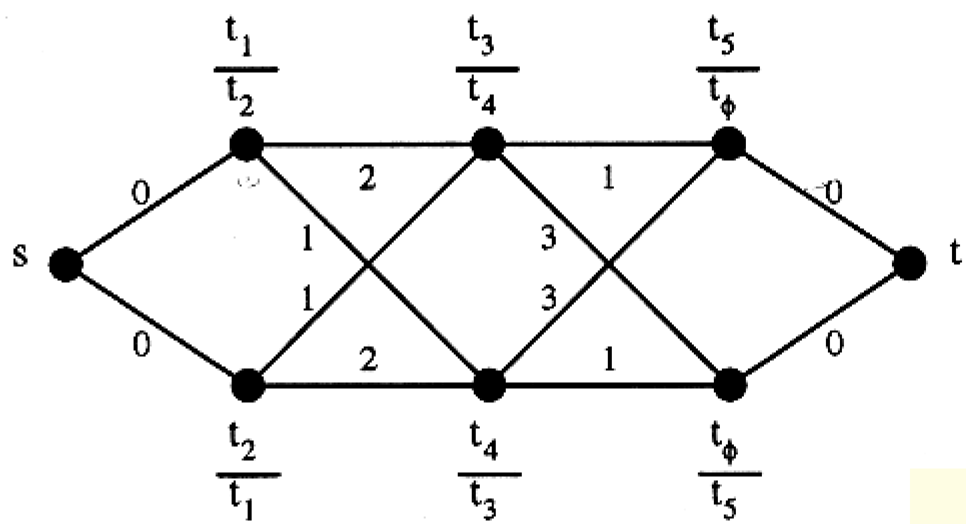
(b)

Track ordering graph

Time	P_1	P_2
1	t_1	t_2
2	t_3	t_4
3	t_5	

(c)

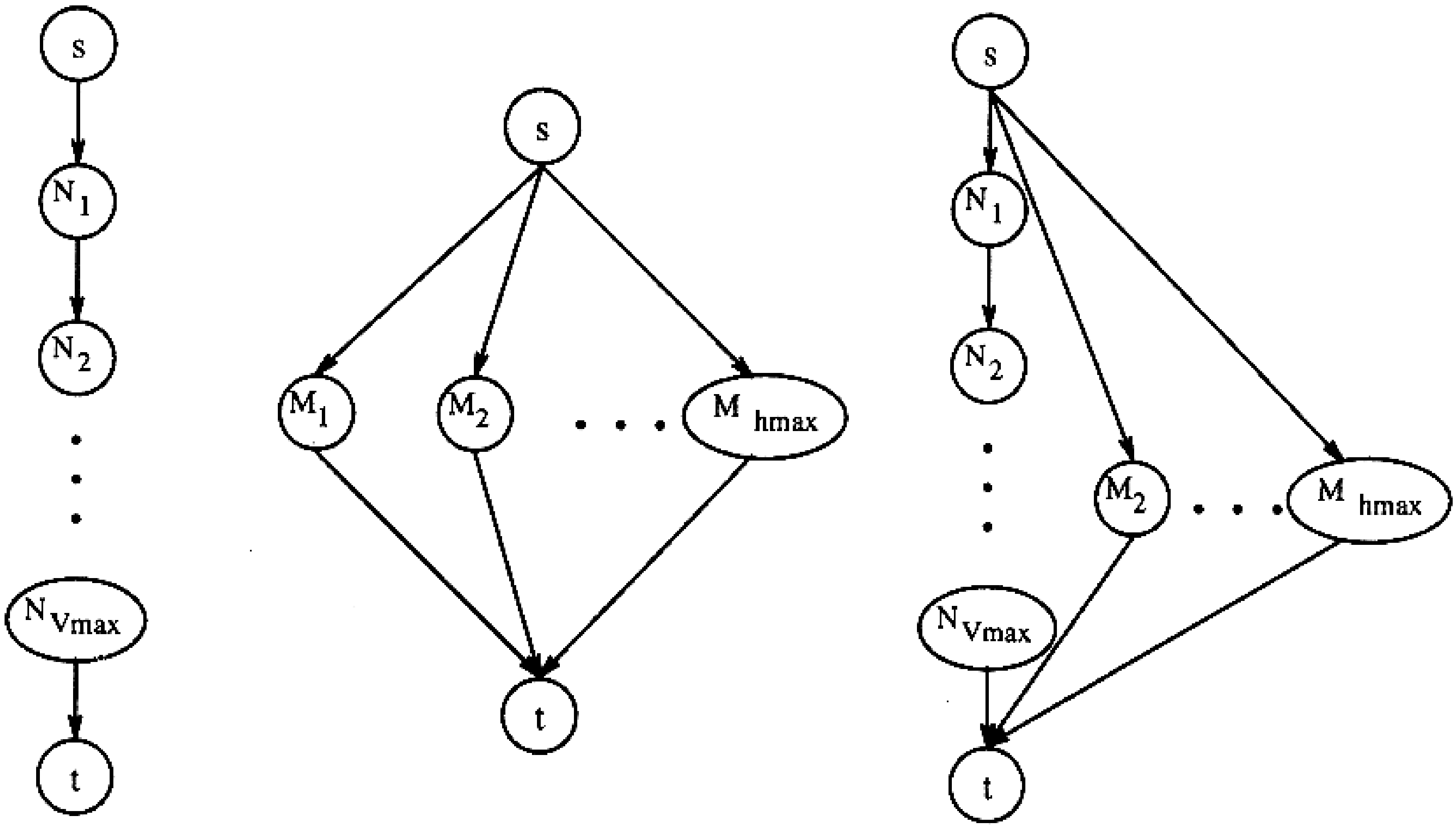
An optimal scheduling solution



(d)

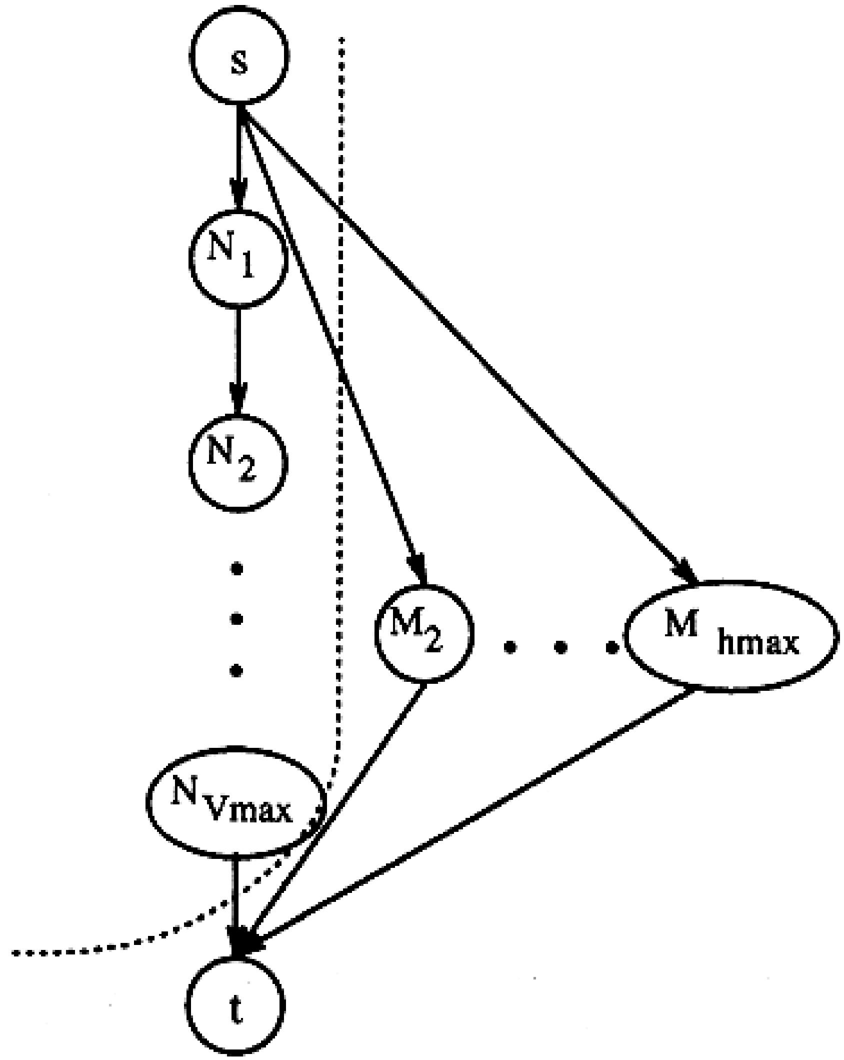
Graph representation

Limitations of HVH or VHV Router



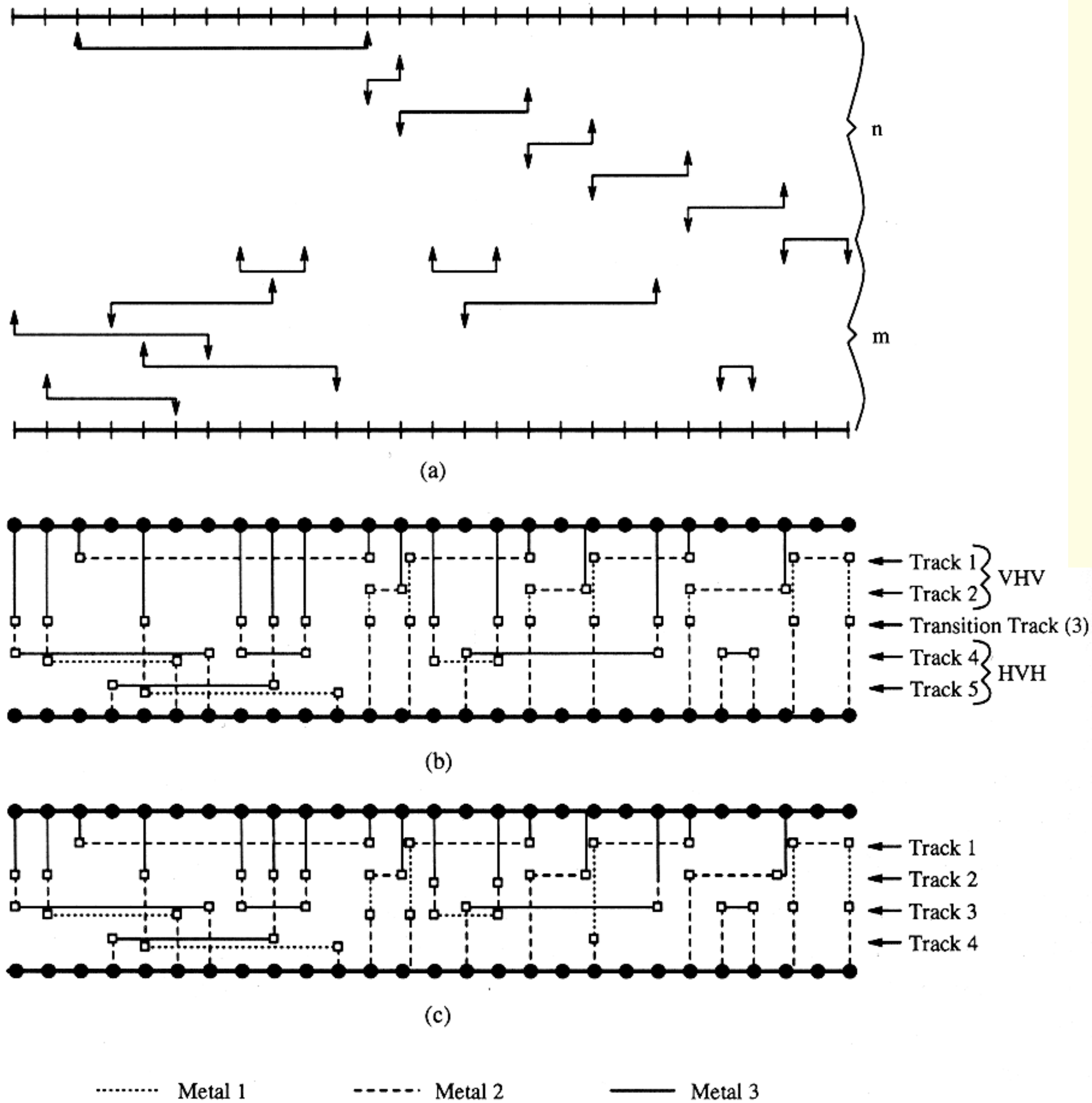
(a) (b) (c)

Partitioning for Hybrid Routing



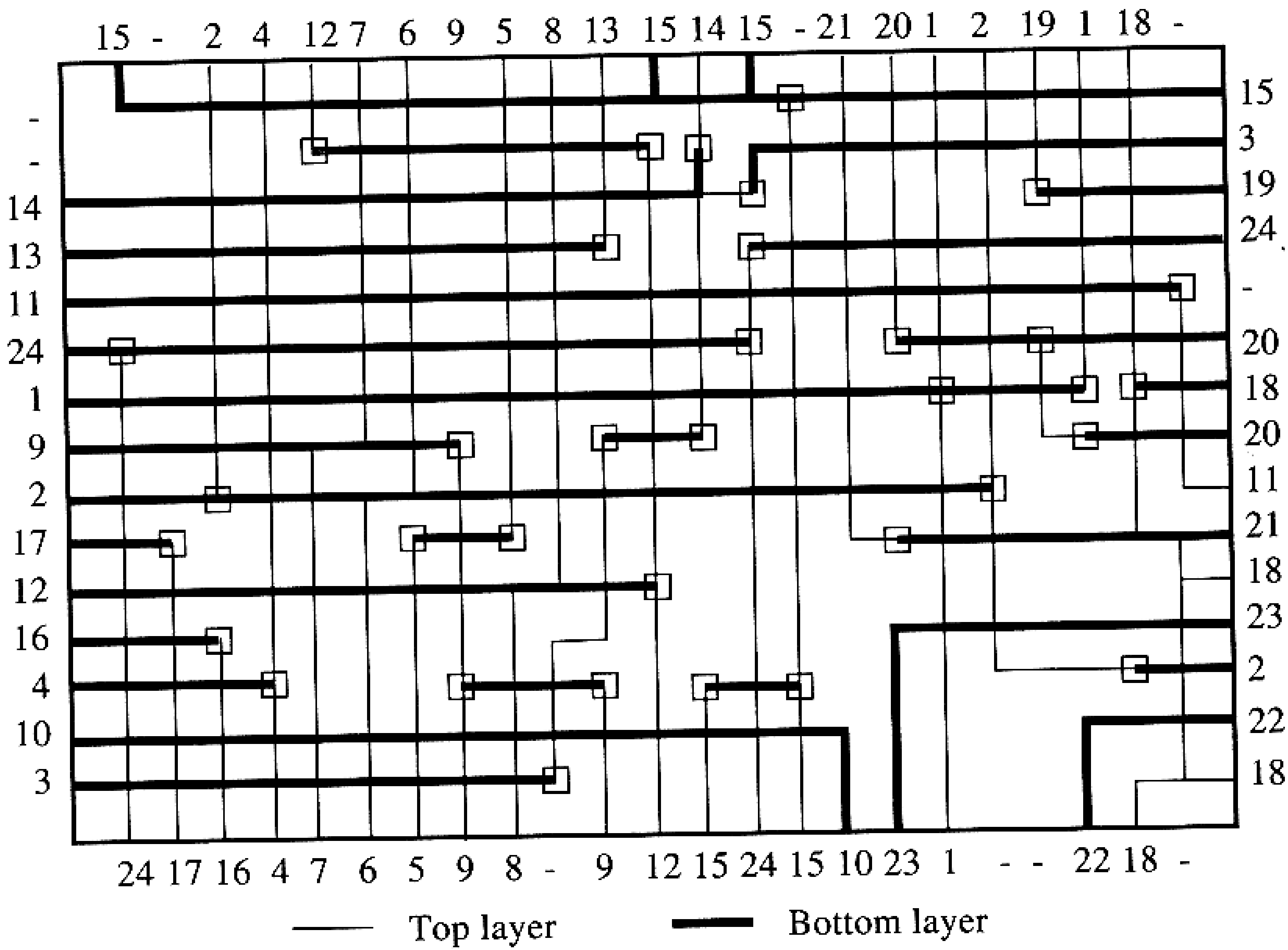
Hybrid HVH-VHV Router

- Uses both HVH and VHV routing schemes.
- Pure HVH and VHV are special cases of Hybrid Router.
- It partitions the channel into two portions – not necessarily of the same size.
  - One portion is for HVH and the other for VHV.
  - One track is required for interconnection between the two portions.


n
m
(a)
Track 1
Track 2
VHV
Transition Track (3)
Track 4
Track 5
HVH
(b)
Track 1
Track 2
Track 3
Track 4
(c)
Metal 1
Metal 2
Metal 3

Switchbox Routing

- A switchbox is a generalization of a channel.
  - Has terminals on all four sides.
- More difficult than channel routing problem.
  - Main objective of channel routing is to minimize the channel height.
  - Main objective of switchbox routing is to ensure that all the nets are routed.
- Classification of algorithms:
  - Greedy router
  - Rip up and reroute routers
  - BEAVER (based on computational geometry)


15 - 2 4 12 7 6 9 5 8 13 15 14 15 - 21 20 1 2 19 1 18 -
- - 14 13 11 24 1 9 2 17 12 16 4 10 3
15 3 19 24 - 20 18 20 11 21 18 23 2 22 18
24 17 16 4 7 6 5 9 8 - 9 12 15 24 15 10 23 1 - - 22 18 -
Top layer
Bottom layer

Summary

- The detailed routing problem is solved by routing the channels and switchboxes.
- Routing results may differ based on the routing model used.
  - Grid-based.
  - Based on assigning layer of different net segments.
- The objectives for routing a channel is to minimize channel density, the length of routing nets, and the number of via's.
- The main objective of channel routing is to minimize the total routing area.
- The objective of switchbox routing is to determine the routability.