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.
The two-stage routing method is a powerful technique for routing.

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.
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 and Switchbox Diagram]

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.
Routing Considerations

• Number of terminals
  – Majority of nets are two-terminal ones.
  – For some nets (viz. clock, 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.

• Via restrictions
  – Regular: only between adjacent layers.
  – Stacked: passing through more than two layers.

• Boundary type
  – Regular: straight border of routing region
  – Irregular: arbitrary

• Number of layers
  – Modern fabrication technology allows at least five layers of routing.

• Net types
  – Critical: power, ground, clock nets
  – Non-critical: signal nets
CMOS Fabrication

NMOS

B
S
G
D
p+
n+
n+
p-substrate

PMOS

S
G
D
B
p+
p+
n+
n-well

Via Connections

Top View

3D View

Side View
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)
Channel Routing

• In channel routing, interconnections are made within a rectangular region having no obstructions.
  – A majority of modern-day ASICs 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

![Diagram of channel routing problem with terminologies and net list]

**Net list**:

<table>
<thead>
<tr>
<th>TOP</th>
<th>BOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1 2 0 2 3]</td>
<td>[3 3 1 1 0]</td>
</tr>
</tbody>
</table>
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 task of the channel router is to:
  – Assign horizontal segments of nets to tracks.
  – Assign vertical segments to connect
    a) Horizontal segments of the same net in different tracks.
    b) The terminals of the net to horizontal segments of the net.

• Channel height should be minimized.
• Horizontal and vertical constraints must be met.
Channel Constraints

- **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.

![Horizontal Constraint Graph](image)
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

- Greedy Channel Router

- Hierarchical Channel Router
Basic Left Edge Algorithm

• Simplest channel routing algorithm.
• Assumptions:
  – Only two-terminal nets.
  – No vertical constraints.
  – HV two-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.
Extension to Left-Edge Algorithm

- Vertical constraints may exist, but there are no directed cycles in the VCG.
- Select a net for routing if both the following conditions are true:
  a) The x-coordinate of the leftmost terminal is the least.
  b) 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 are the same as the basic left-edge algorithm.
Dogleg Router

• Drawback of LEA:
  – 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.

• Dogleg router allows multi-terminal nets and vertical constraints.
  – Multi-terminal nets are broken into a series of two-terminal nets.

• Cannot handle cyclic vertical constraints.
Dogleg Example

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.
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.

Key Steps of the Algorithm

a) Zone representation  
b) Net merging  
c) Track assignment
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

<table>
<thead>
<tr>
<th>Column</th>
<th>$S(i)$</th>
<th>Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>{2}</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>{1,2,3}</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>{1,2,3,4,5}</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>{1,2,3,4,5}</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>{1,2,4,5}</td>
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</tr>
<tr>
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</tr>
<tr>
<td>8</td>
<td>{4,7,8}</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>{4,7,8,9}</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>{7,8,9}</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>{7,9,10}</td>
<td>5</td>
</tr>
<tr>
<td>12</td>
<td>{9,10}</td>
<td></td>
</tr>
</tbody>
</table>

### Zone Representation

<table>
<thead>
<tr>
<th>Zone</th>
<th>Z1</th>
<th>Z2</th>
<th>Z3</th>
<th>Z4</th>
<th>Z5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
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<tr>
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<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### VCG

- Zone $Z_1$: Column 1
- Zone $Z_2$: Column 2, 3, 4
- Zone $Z_3$: Column 5
- Zone $Z_4$: Column 6
- Zone $Z_5$: Column 7, 8, 9, 10

- Zone $Z_6$: Column 11
- Zone $Z_7$: Column 12
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 be merged to form a new composite net.
  - Modifies VCG by merging nodes $v_i$ and $v_j$ into a single node $v_{ij}$.
  - Modifies HCG / zone representation by replacing nodes $v_i$ and $v_j$ by a net $v_{ij}$, which occupies the consecutive zones including those of nets $N_i$ and $N_j$.

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

• 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
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.

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

Comparison of Two-Layer Channel Routers

<table>
<thead>
<tr>
<th></th>
<th>LEA</th>
<th>Dogleg</th>
<th>Net Merge</th>
<th>Greedy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Grid-based</td>
<td>Grid-based</td>
<td>Grid-based</td>
<td>Grid-based</td>
</tr>
<tr>
<td>Dogleg</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Vertical constraint</td>
<td>No / Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Cyclic constraint</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Three-Layer Channel Routing

• 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 to form super-composite nets.
• Objective:
  – Reduce the number of super-composite nets.
• 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.
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)
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 total routing area.

• The objective of switchbox routing is to determine the routability.
Over-The-Cell Routing

Introduction

• Used in sophisticated channel routers in standard cell based designs.
• Basic idea:
  – Use of area outside the channel to obtain reduction in channel height.
  – Routing over the cell rows is possible due to limited use of the second and third metal layers.
Basic Steps in OTC Routing

• **Step 1:** Net decomposition
  – Each multi-terminal net is partitioned into a set of 2-terminal nets (defined based on x-coordinates of their left ends).

• **Step 2:** Net classification
  – Each net is classified into one of following types:
    • **Type 1:** There is a vacant terminal directly opposite to one of the terminals of the net.
    • **Type 2:** There is a vacant terminal between the two terminals of the net.
    • **Type 3:** None of the above.

• **Step 3:** Vacant terminal assignment
  – Vacant terminals are assigned to each net depending on its type and weight.
  – Weight of a net is defined as the improvement in channel congestion possible if this net can be routed over the cell.

• **Step 4:** Over-the-cell routing
  – The selected nets are assigned exact geometric paths for routing in the area over the cells.

• **Step 5:** Channel segment assignment & routing
  – Selects the best net segments to be routed in the channel.
  – Route them using any available channel router.
Example

Greedy channel router

OTC routing