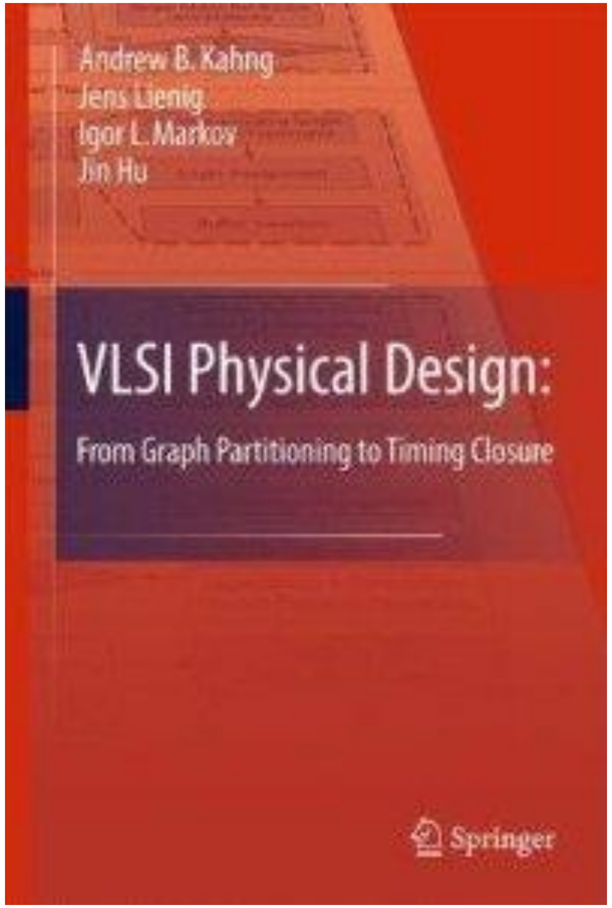
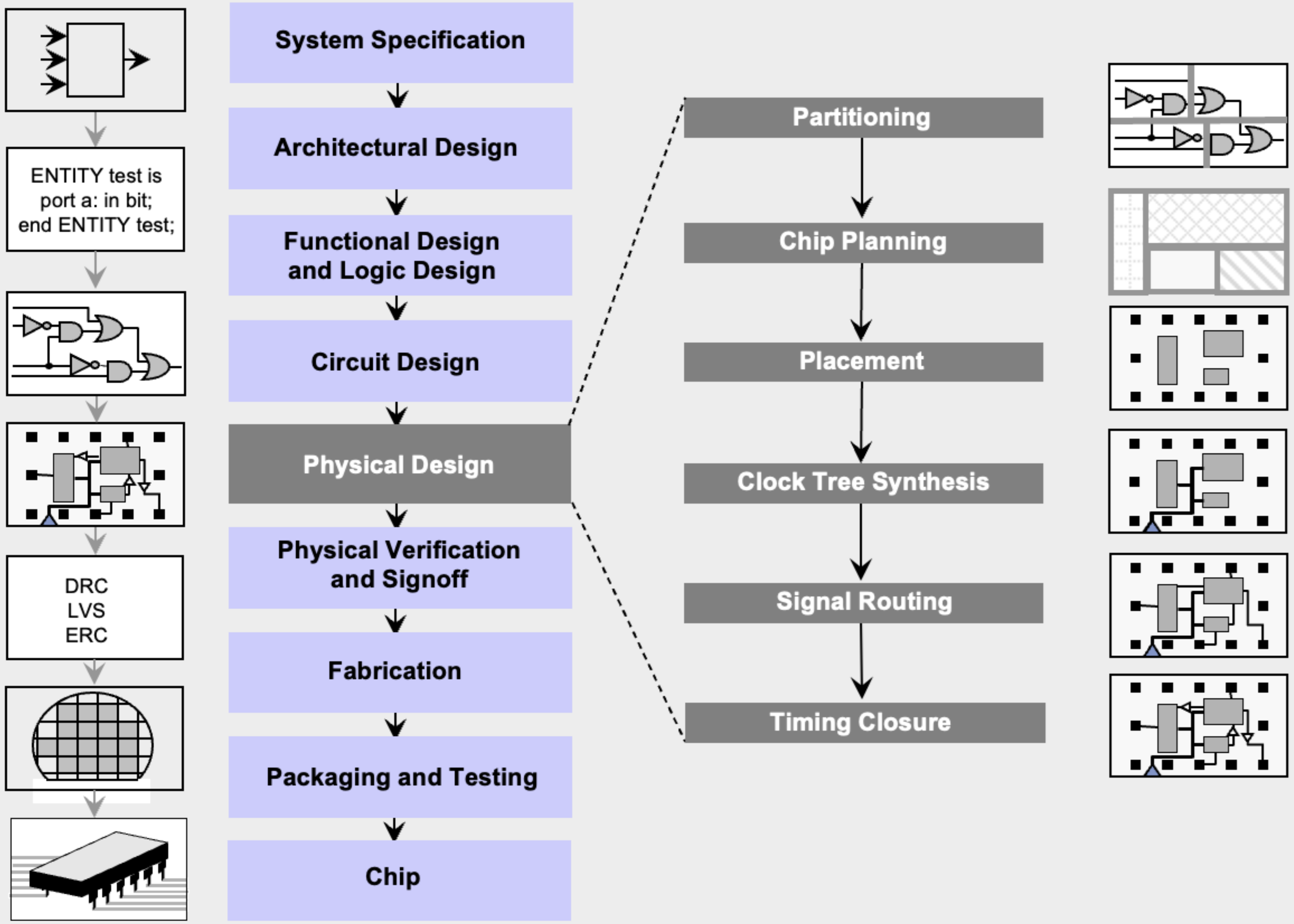


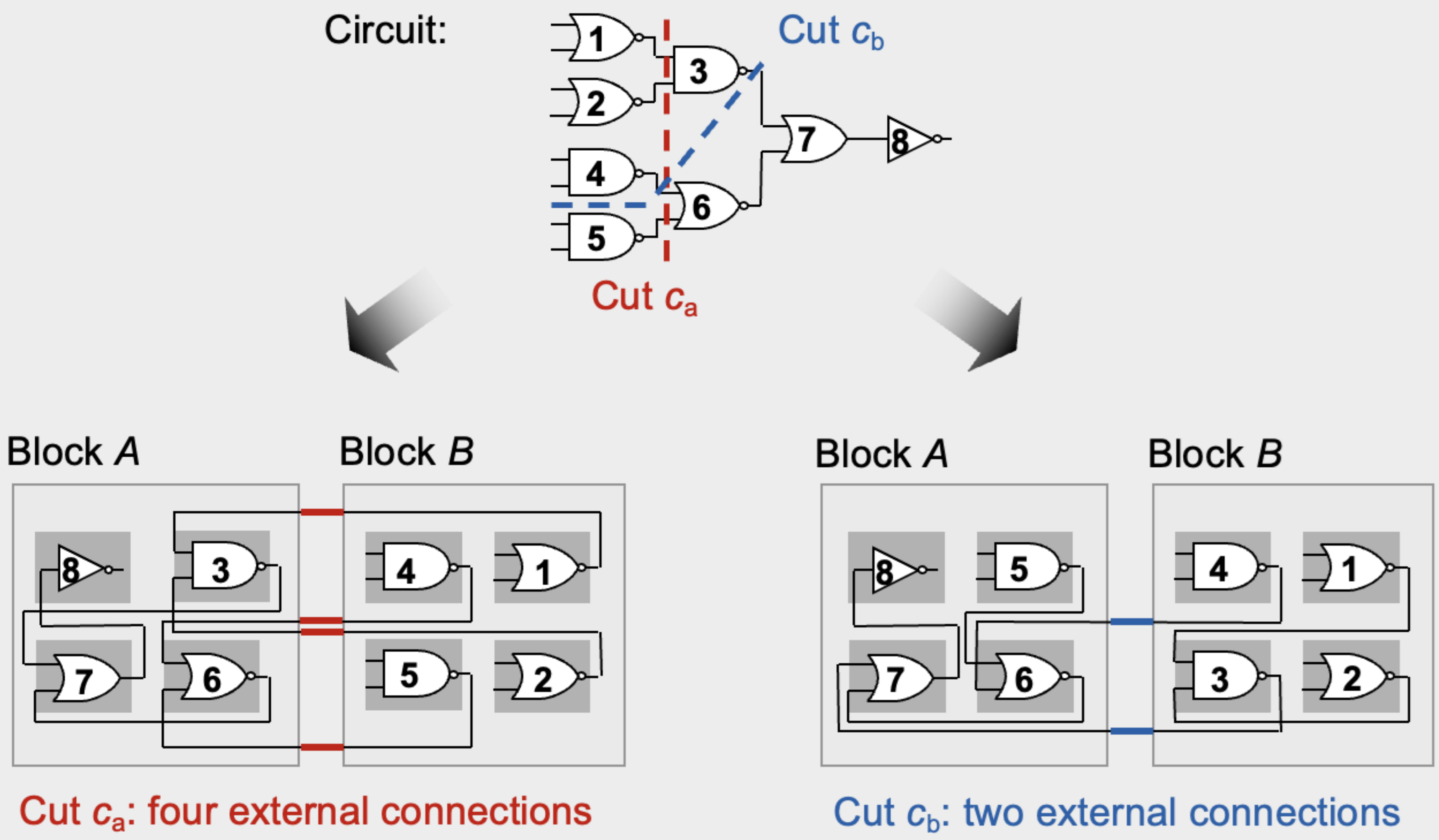
CSE 460: VLSI Design

Lecture 13+14: VLSI Physical Design

VLSI Design Flow

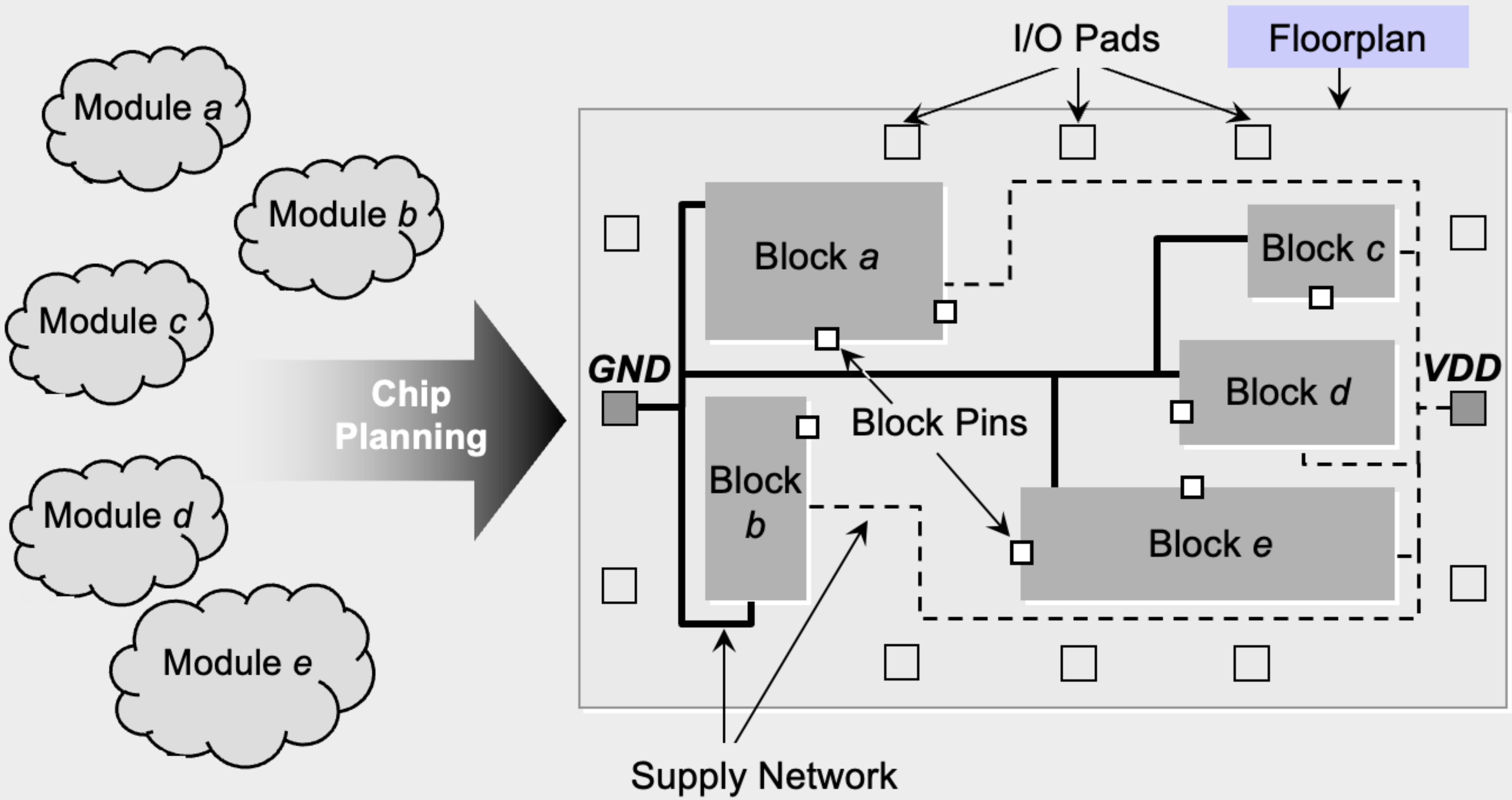


Partitioning



Algorithms Involved: Kernighan-Lin (KL) Algorithm, Fiduccia-Mattheyses (FM) Algorithm

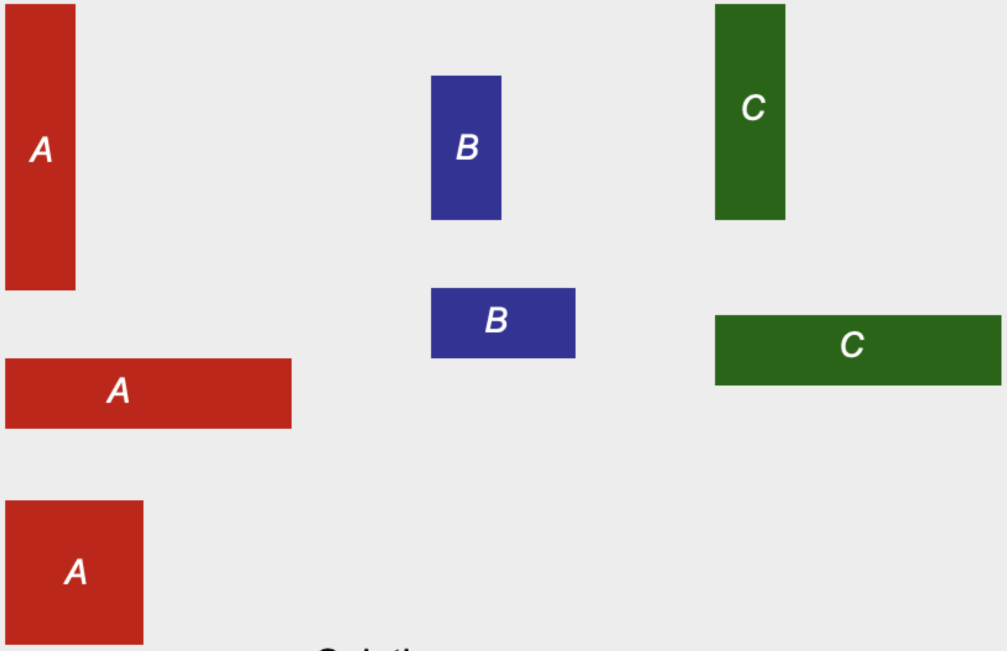
Chip Planning

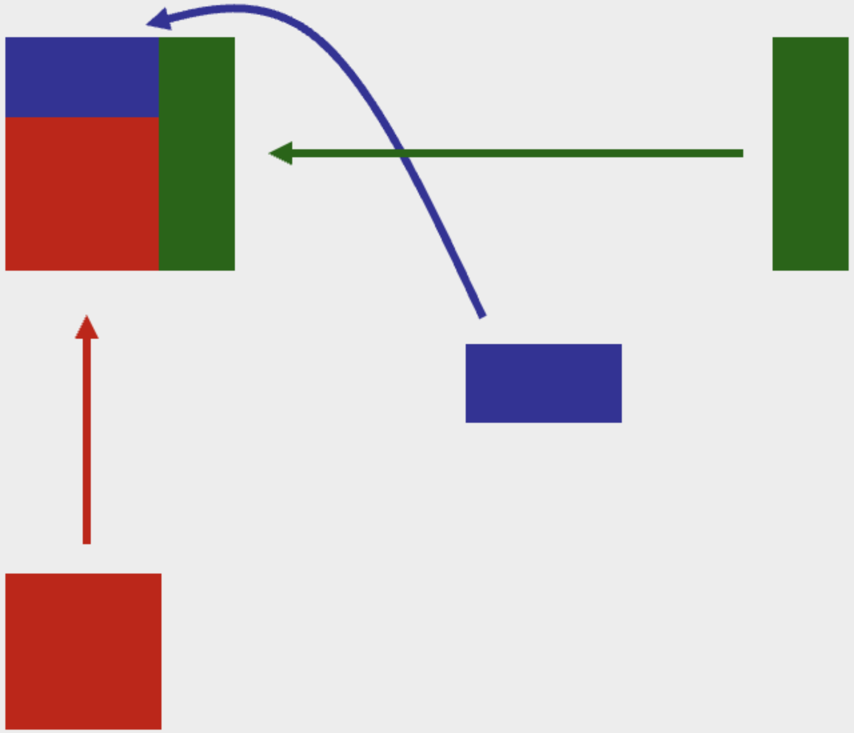


Chip Planning (Example)

Given: Three blocks with the following potential widths and heights
Block A: $w = 1$, $h = 4$ or $w = 4$, $h = 1$ or $w = 2$, $h = 2$
Block B: $w = 1$, $h = 2$ or $w = 2$, $h = 1$
Block C: $w = 1$, $h = 3$ or $w = 3$, $h = 1$

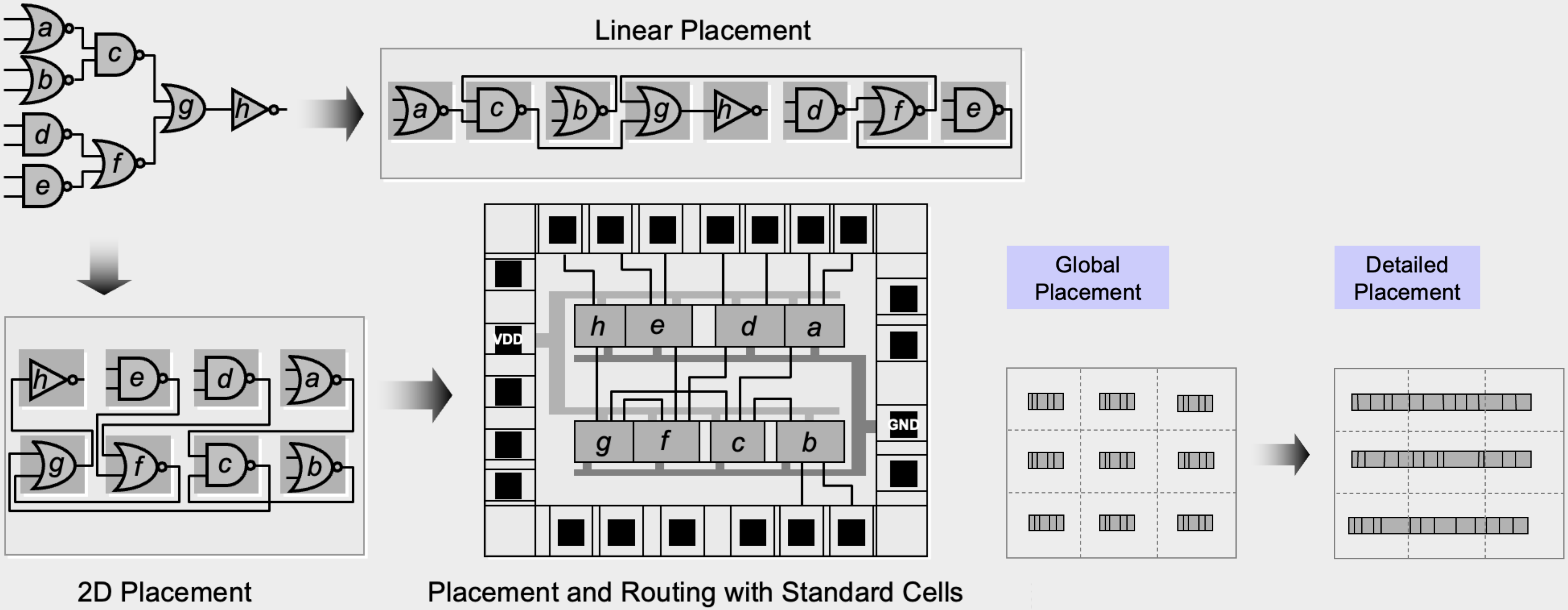
Task: Floorplan with minimum total area enclosed





Solution:
Aspect ratios
Block A with $w = 2$, $h = 2$; Block B with $w = 2$, $h = 1$; Block C with $w = 1$, $h = 3$

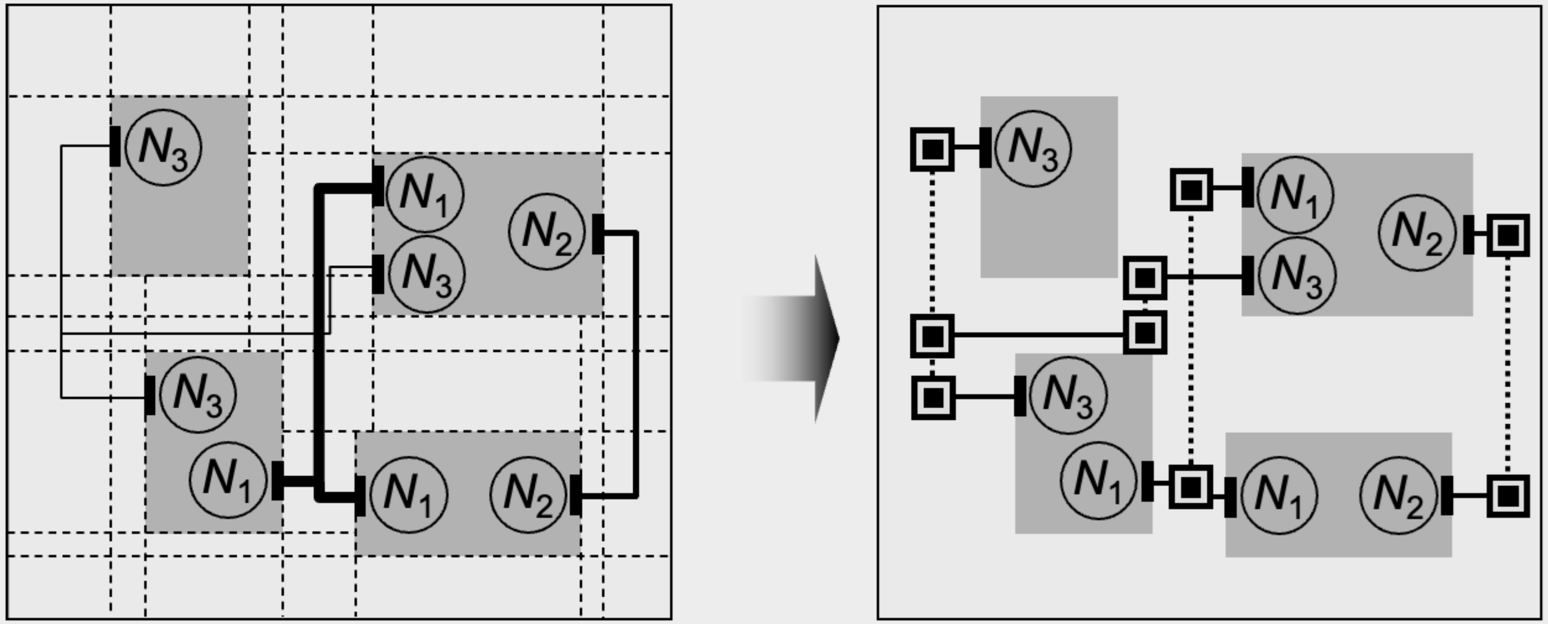
Placement


a
b
c
d
e
f
g
h
Linear Placement
a
c
b
g
h
d
f
e
h
e
d
a
VDD
GND
g
f
c
b
Global
Placement
Detailed
Placement
2D Placement
Placement and Routing with Standard Cells

Signal Routing

Global Routing

Detailed Routing



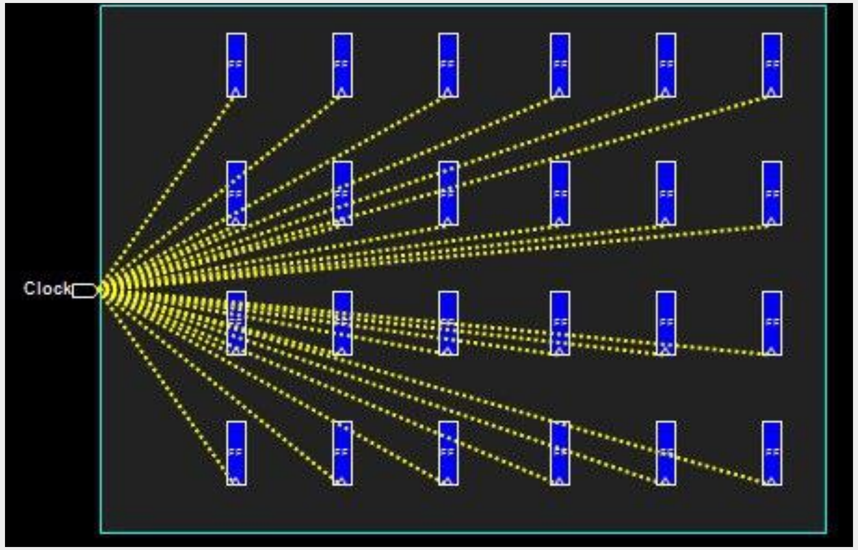
Horizontal connection with Metal 1
Horizontal connection with Metal 2

Metal to Metal connections are made with Via

Clock Tree Synthesis (CTS)

Definition:

- ❖ Clock tree synthesis is a process which make sure that the clock gets distributed evenly to all sequential elements in a design.
- ❖ CTS is the process of insertion of buffers or inverters along the clock paths of ASIC design in order to achieve minimum skew or balanced skew.
- ❖ In ICs, clock consumes around half of the total power consumption. Here clock gating technique helps to reduce power consumption by the clocks.



Goals of CTS:

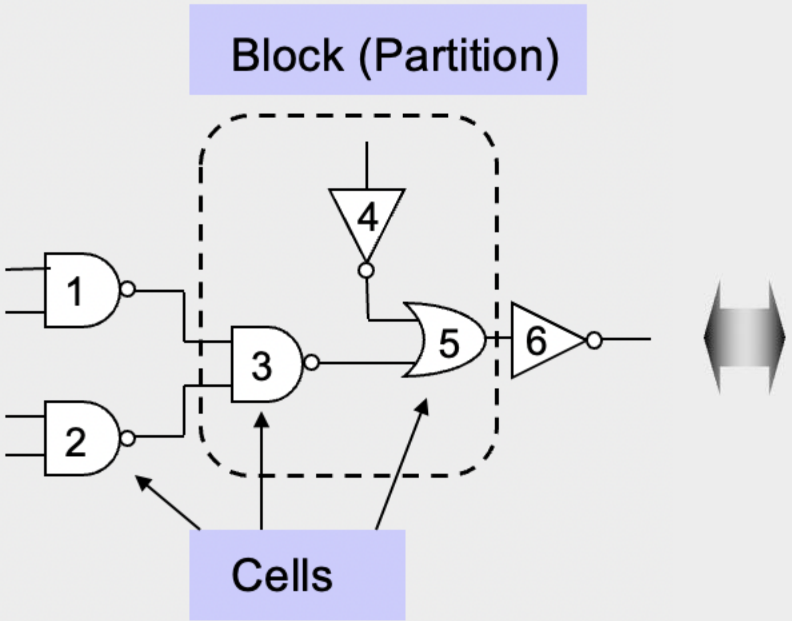
- ❖ To meet clock tree design rule constraints such as maximum transition, maximum load capacitance and maximum fanout.
- ❖ To meet clock tree targets such as minimum skew and minimum insertion delay.

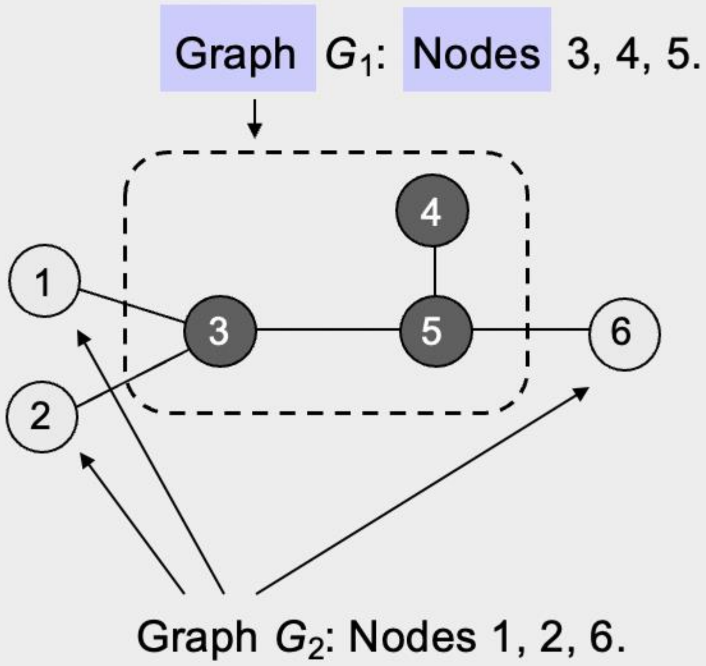
Timing Closure

- ❖Timing closure is the process by which a logic design consisting of primitive elements such as combinatorial logic gates (and , or , not , nand , nor , etc.) and sequential logic gates (flip flops, latches, memories) is modified to meet its timing requirements.

- ❖Timing closure is done through layout optimizations and netlist modifications.

Partition Terminology





Edge – Number of connections. (a) Cut edge: Inter-module connections
(b) Non cut edge: Intra-model connections

$E(3) = 3$, $E_c(3) = 2$, $E_{nc}(3) = 1$
Cost of moving a node, $D = E_c – E_{nc}$
$D(2) = 1-0 = 1$, $D(3) = 2-1 = 1$, $D(4) = 0-1 = -1$ (Negative is possible)

Gain in swapping the nodes a and b, $\Delta g(a,b) = D(a) + D(b) – 2c(a,b)$
where $c(a,b)$ = number of connections between a and b. Usually its 1 when nodes are connected and 0 when not connected. $\Delta g(3,6) = 1 + 1 – 2*0 = 2$
Gain is mainly calculated for inter module nodes.

Collection of cut edges

Cut set: (1,3), (2,3), (5,6),

Cut set means inter-module connections set
Cut cost is the number of inter-module connections or the number of elements in the cut set.
In this initial assumption, the cut cost is 3

Optimization Goals

- Given a graph $G(V,E)$ with $|V|$ nodes and $|E|$ edges where each node $v \in V$ and each edge $e \in E$.

- Each node has area $s(v)$ and each edge has cost or weight $w(e)$.

- The objective is to divide the graph G into k disjoint subgraphs such that all optimization goals are achieved and all original edge relations are respected.

Optimization Goals

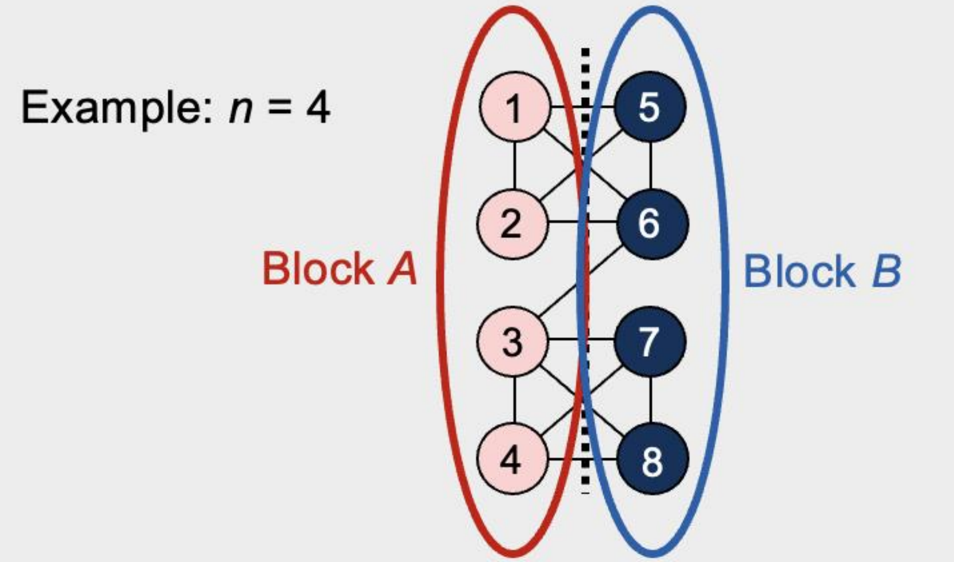
- In detail, what are the optimization goals?
  - Number of connections between partitions is minimized
  - Each partition meets all design constraints (size, number of external connections..)
  - Balance every partition as well as possible

- How can we meet these goals?
  - Unfortunately, this problem is NP-hard
  - Efficient heuristics are developed in the 1970s and 1980s. They are high quality and in low-order polynomial time.

Kernighan Lin (KL Algorithm)

Given: A graph with 2*n* nodes where each node has the same weight.

Goal: A partition (division) of the graph into two disjoint subsets *A* and *B* with minimum cut cost and $|A| = |B| = n$.



KL Algorithm (Terminology)

Cost $D(v)$ of moving a node v

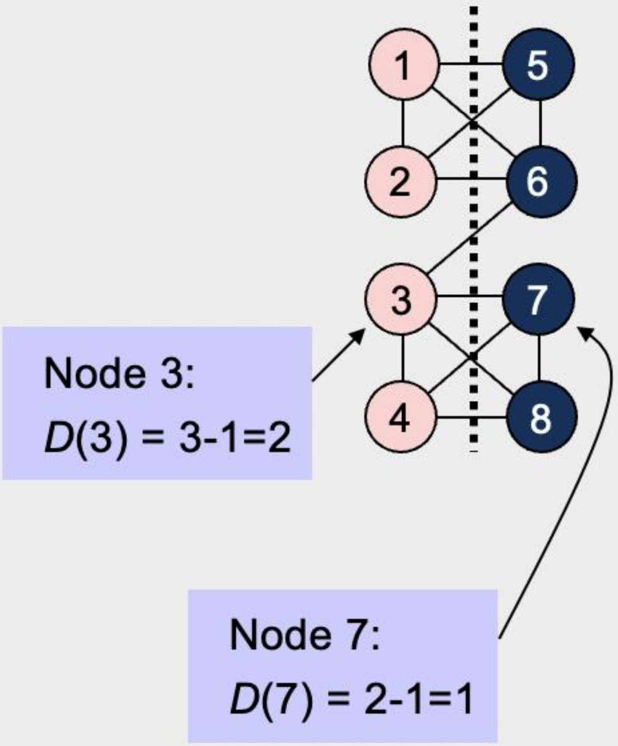
$$D(v) = |E_c(v)| - |E_{nc}(v)| \ ,$$

where

$E_c(v)$ is the set of v's incident edges that are cut by the cut line, and

$E_{nc}(v)$ is the set of v's incident edges that are not cut by the cut line.

High costs ($D > 0$) indicate that the node should move, while low costs ($D < 0$) indicate that the node should stay within the same partition.



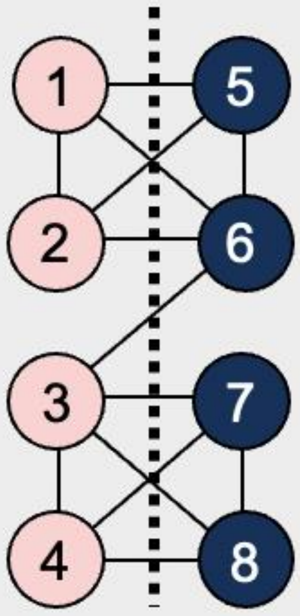
KL Algorithm (Terminology)

Gain of swapping a pair of nodes *a* und *b*

$\Delta g = D(a) + D(b) - 2 * c(a,b)$,

where

- $D(a)$, $D(b)$ are the respective costs of nodes *a*, *b*
- $c(a,b)$ is the connection weight between *a* and *b*:
  If an edge exists between *a* and *b*,
  then $c(a,b)$ = edge weight (here 1),
  otherwise, $c(a,b) = 0$.



The gain Δg indicates how useful the swap between two nodes will be

The larger Δg, the more the total cut cost will be reduced

KL Algorithm (Terminology)

Gain of swapping a pair of nodes *a* und *b*

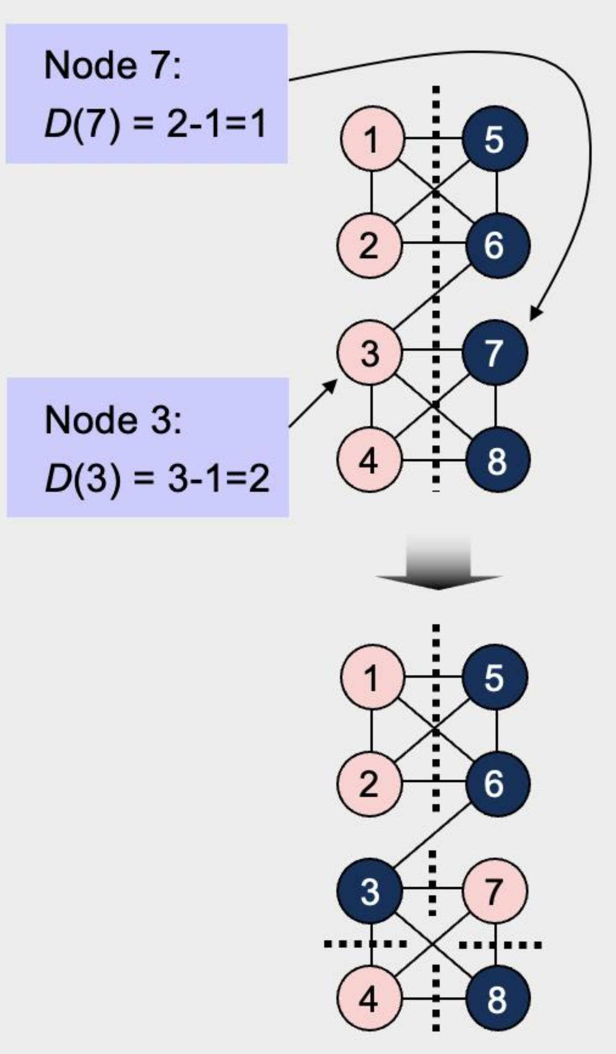
$\Delta g = D(a) + D(b) - 2 * c(a,b),$

where

- $D(a)$, $D(b)$ are the respective costs of nodes *a*, *b*
- $c(a,b)$ is the connection weight between *a* and *b*:
  If an edge exists between *a* and *b*,
  then $c(a,b)$ = edge weight (here 1),
  otherwise, $c(a,b) = 0$.

$\Delta g\ (3,7) = D(3) + D(7) - 2 * c(a,b) = 2 + 1 - 2 = 1$

=> Swapping nodes 3 and 7 would reduce the cut size by 1



KL Algorithm (Terminology)

Gain of swapping a pair of nodes *a* und *b*

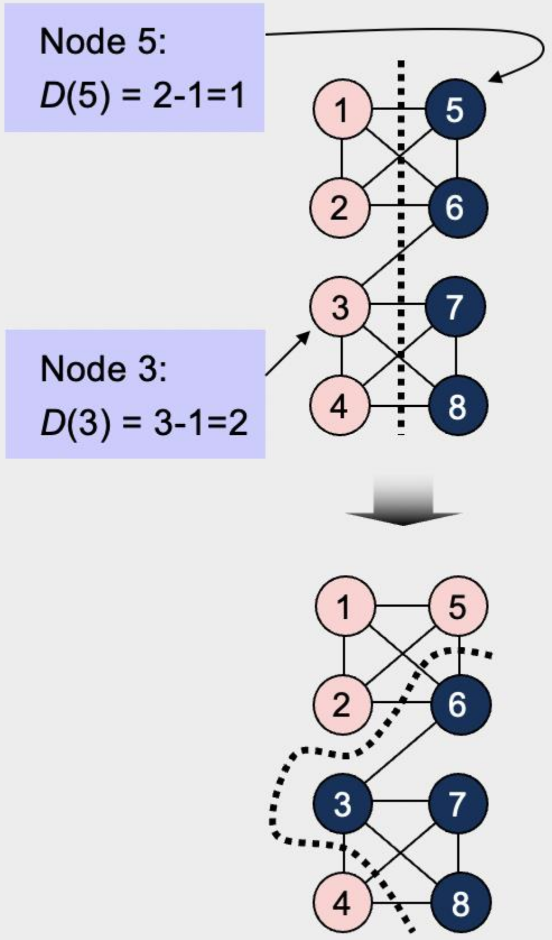
$$\Delta g = D(a) + D(b) - 2 * c(a,b),$$

where

- $D(a)$, $D(b)$ are the respective costs of nodes *a*, *b*
- $c(a,b)$ is the connection weight between *a* and *b*:
  If an edge exists between *a* and *b*,
  then $c(a,b)$ = edge weight (here 1),
  otherwise, $c(a,b) = 0$.

$$\Delta g\ (3,5) = D(3) + D(5) - 2 * c(a,b) = 2 + 1 - 0 = 3$$

=> Swapping nodes 3 and 5 would reduce the cut size by 3



KL Algorithm (Terminology)

Gain of swapping a pair of nodes *a* und *b*

The goal is to find a pair of nodes *a* and *b* to exchange such that Δg is maximized and swap them.

Maximum positive gain G_m of a pass

The maximum positive gain G_m corresponds to the best prefix of *m* swaps within the swap sequence of a given pass.

These *m* swaps lead to the partition with the minimum cut cost encountered during the pass.

$$G_m = \sum_{i=1}^{m} \Delta g_i$$

G_m is computed as the sum of Δg values over the first *m* swaps of the pass, with *m* chosen such that G_m is maximized.

KL Algorithm (One-pass)

Step 0:
- $V = 2n$ nodes
- $\{A, B\}$ is an initial arbitrary partitioning

Step 1:
- $i = 1$
- Compute $D(v)$ for all nodes $v \in V$

Step 2:
- Choose a_i and b_i such that $\Delta g_i = D(a_i) + D(b_i) - 2 * c(a_i b_i)$ is maximized
- Swap and fix a_i and b_i

Step 3:
- If all nodes are fixed, go to Step 4. Otherwise
- Compute and update D values for all nodes that are connected to a_i and b_i and are not fixed.
- $i = i + 1$
- Go to Step 2

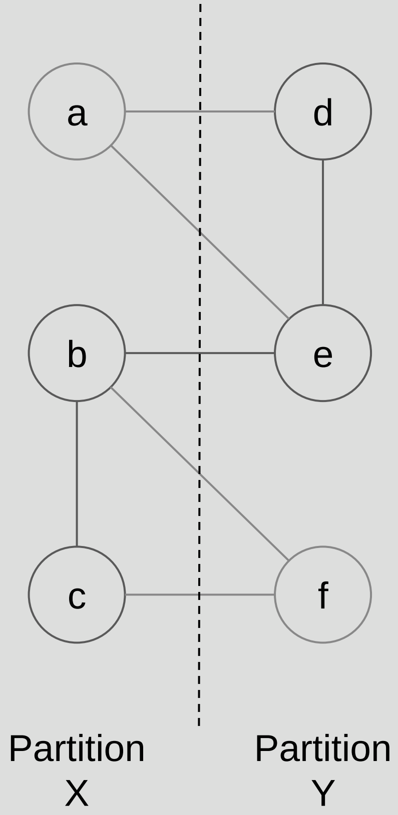
Step 4:
- Find the move sequence $1...m$ $(1 \le m \le i)$, such that $G_m = \sum_{i=1}^{m} \Delta g_i$ is maximized
- If $G_m > 0$, go to Step 5. Otherwise, END

Step 5:
- Execute m swaps, reset remaining nodes
- Go to Step 1

KL Algorithm (Example 1)

The graph (nodes a-f) can be optimally partitioned using the Kernighan-Lin algorithm. The dotted line represents the initial partitioning. Assume all the edges have the same weight.

a. What is the initial cut cost?
b. Perform the first pass of the algorithm.
   [*Hint: For the "i"th iteration of the first pass, until all the nodes are swapped and fixed, do the following:*
   i. *Compute/update the node costs of all unfixed nodes*
   ii. *Find the maximum gain of swapping a pair of nodes* (Δg_i)
   iii. *Swap the pair and draw the updated graph*]
c. Finish the first pass by computing the maximum positive gain, G_m. Suggest how many swaps should be actually executed in the first pass.
d. Should you perform subsequent passes of the algorithm? Why or why not?

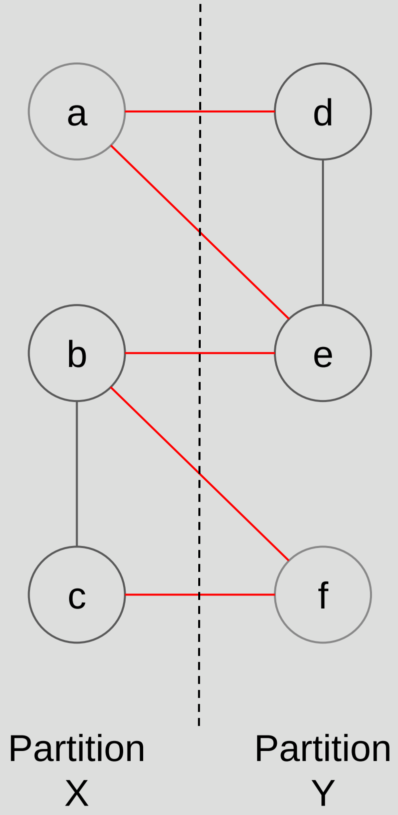


KL Algorithm (Example 1)

The graph (nodes a-f) can be optimally partitioned using the Kernighan-Lin algorithm. The dotted line represents the initial partitioning. Assume all the edges have the same weight.

a. What is the initial cut cost?

Ans: We can see that the initial partition line intersects 5 edges of the graph (shown in **red**). So the initial cut cost is **5**.



KL Algorithm (Example 1)

The graph (nodes a-f) can be optimally partitioned using the Kernighan-Lin algorithm. The dotted line represents the initial partitioning. Assume all the edges have the same weight.

b. Perform the first pass of the algorithm.

For the "i=1" iteration of the first pass:

i. *Compute the node costs of all unfixed nodes*

Ans: D(a) = 2 - 0 = 2; D(b) = 2 - 1 = 1; D(c) = 1 - 1 = 0;

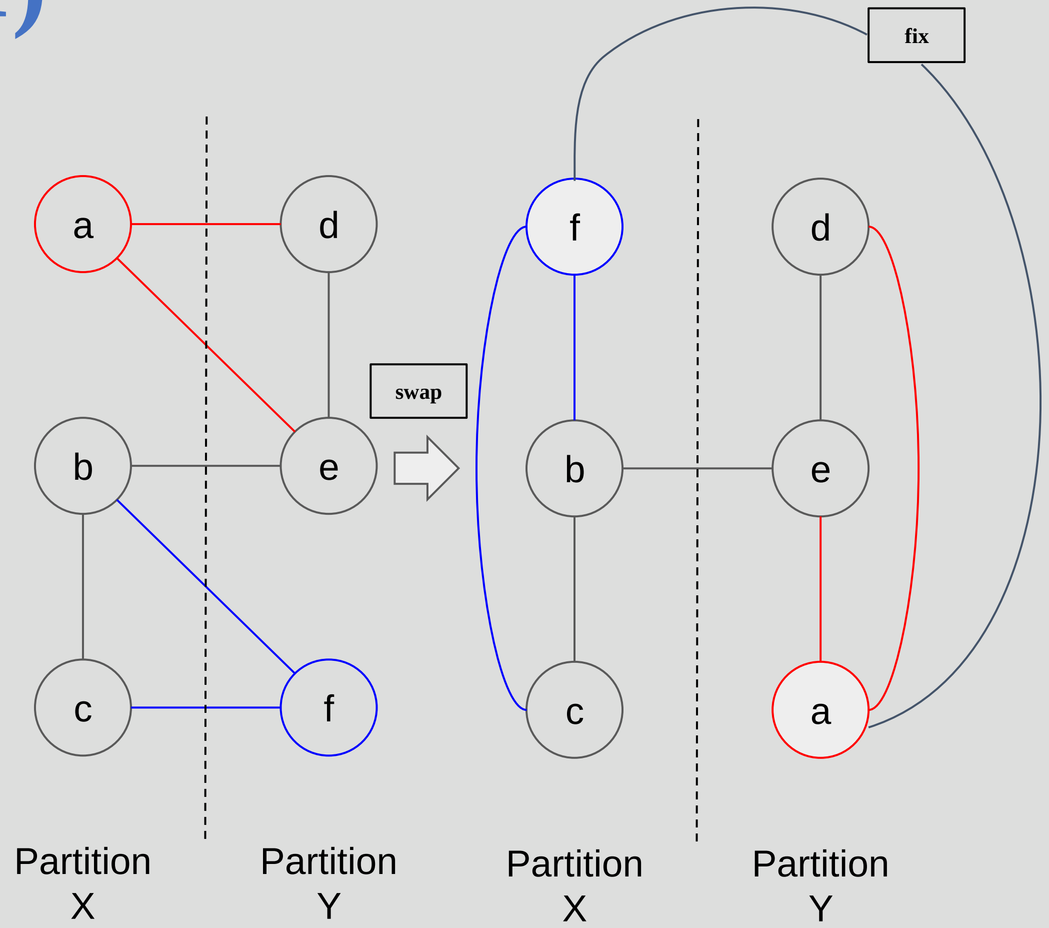
D(d) = 1 - 1 = 0; D(e) = 2 - 1 = 1; D(f) = 2 - 0 = 2.

i. *Find the maximum gain of swapping a pair of nodes (Δg_i)*

Ans: $\Delta g_1(a, f) = 2 + 2 - 0 = 4$.

i. *Swap the pair and draw the updated graph*

Ans: Swap nodes a & f, and fix them.



Initial partition

Partition after completing the $i=1^{st}$ iteration

KL Algorithm (Example 1)

b. Perform the first pass of the algorithm.

For the "i=2" iteration of the first pass:

i. *Update the node costs of all unfixed nodes*

Ans: ~~D(a) = 2 - 0 = 2~~; D(b) = 1 - 2 =-1; D(c) = 0 - 2 =-2;

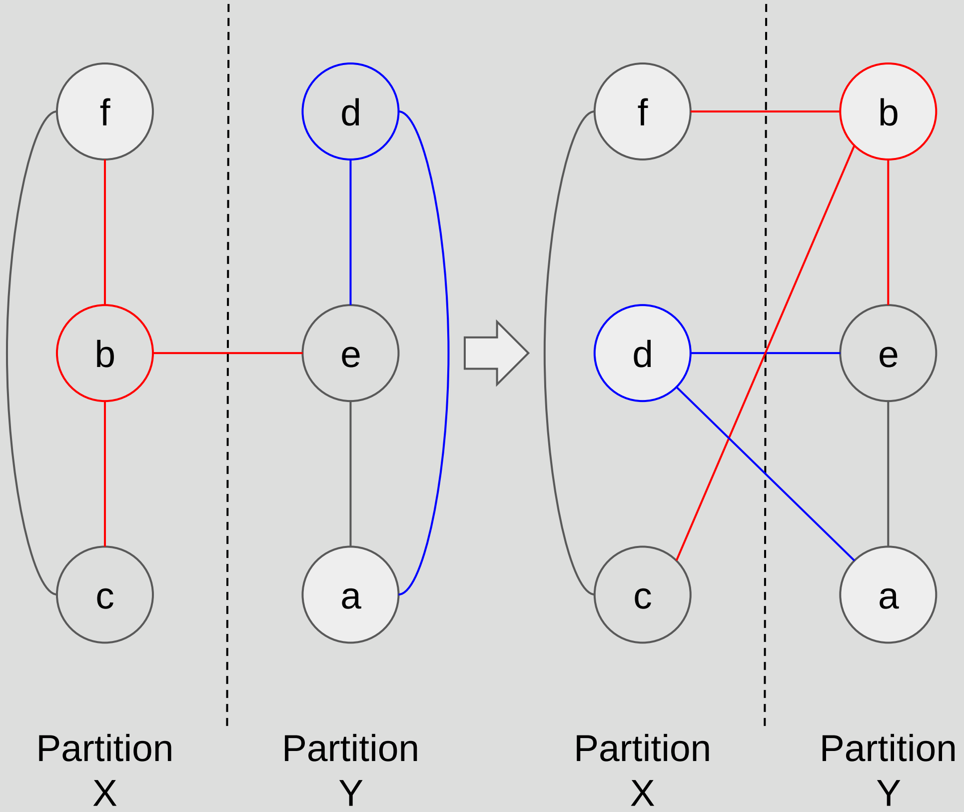
D(d) = 0 - 2 =-2; D(e) = 1 - 2 =-1; ~~D(f) = 2 - 0 = 2~~.

i. *Find the maximum gain of swapping a pair of nodes (Δg_i)*

Ans: $\Delta g_2(b, d)$ = -1 -2 -0 = -3 or $\Delta g_2(c, e)$ = -2 -1 -0 = -3

i. *Swap the pair and draw the updated graph*

Ans: Swap nodes b & d, and fix them or c & e, and fix them. [Both approaches are valid and will end in the same result.]



Partition after completing the i=1st iteration

Partition after completing the i=2nd iteration

KL Algorithm (Example 1)

b. Perform the first pass of the algorithm.

For the "i=3" iteration of the first pass:

i. *Update the node costs of all unfixed nodes*

Ans: ~~D(a) = 2 - 0 = 2~~; ~~D(b) = 1 - 2 =-1~~; D(c) = 1 - 1 = 0;

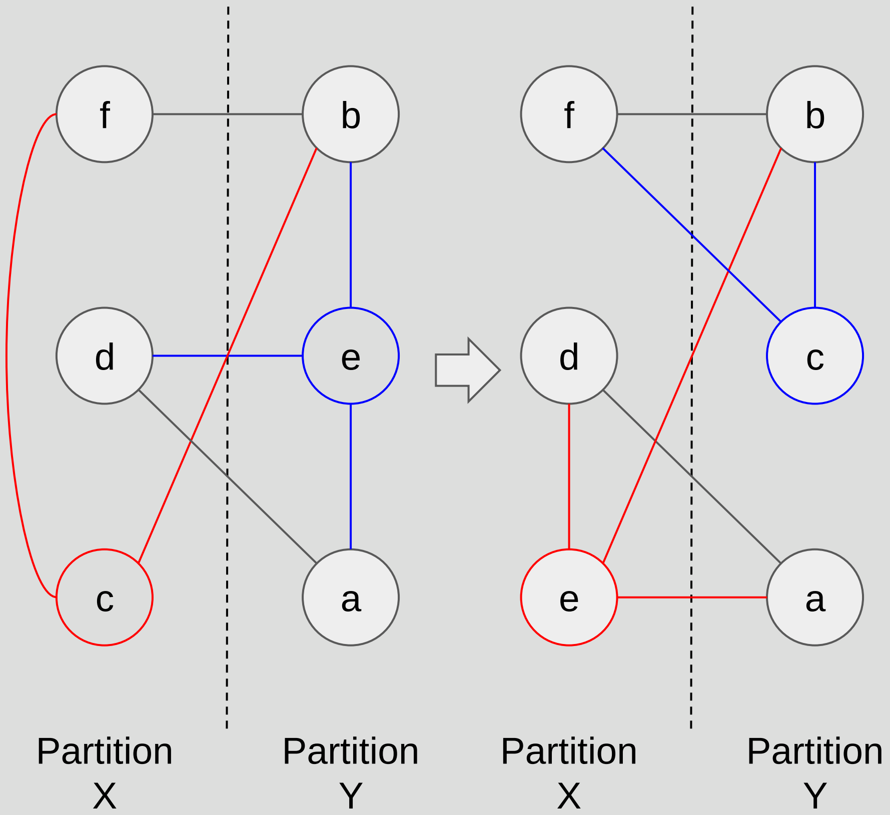
~~D(d) = 1 - 1 = 0~~; D(e) = 1 - 2 =-1; ~~D(f) = 2 - 0 = 2~~.

i. *Find the maximum gain of swapping a pair of nodes (Δg_i)*

Ans: Δg_3(c, e) = 0 -1 - 0 = -1

i. *Swap the pair and draw the updated graph*

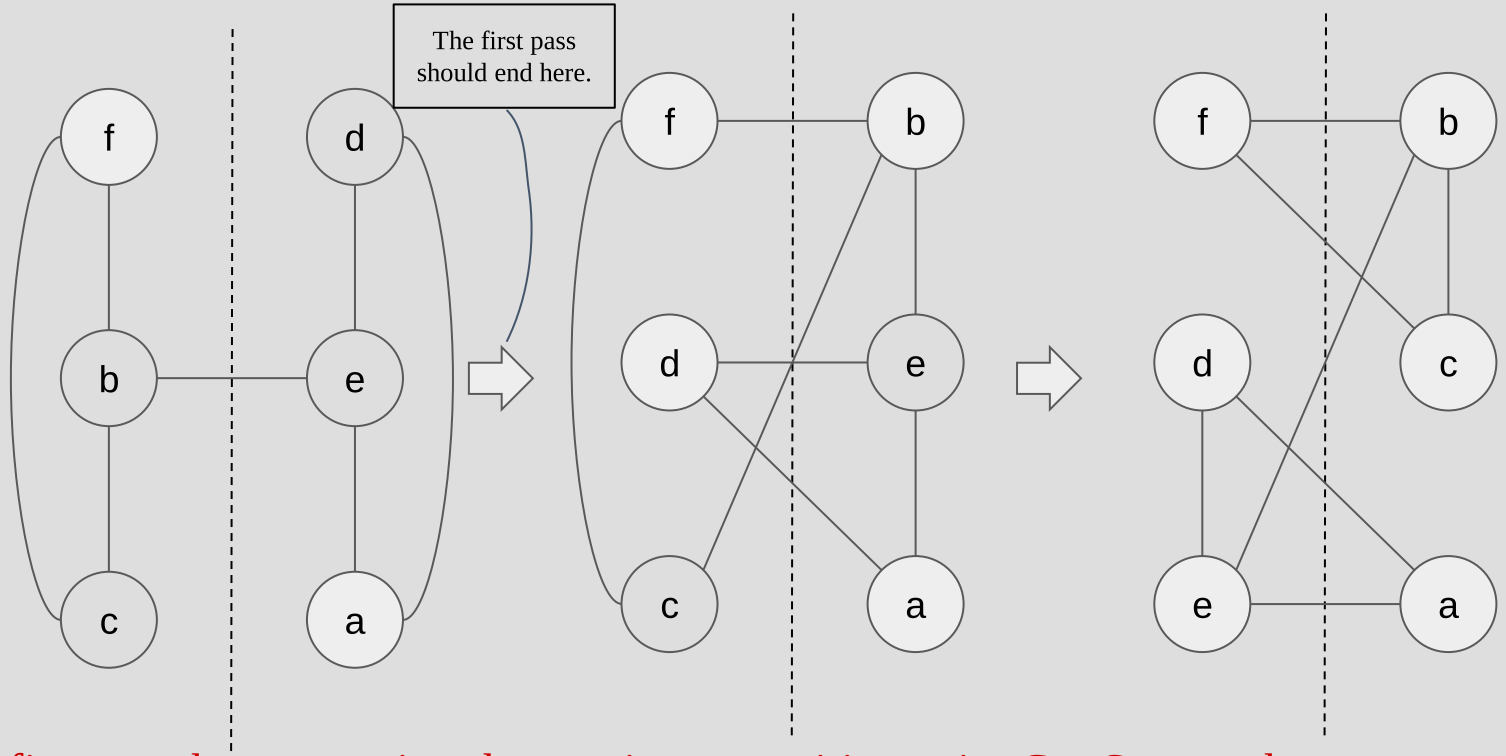
Ans: Swap nodes c & e, and fix them.



Partition after completing the i=2nd iteration

Partition after completing the i=3rd iteration

KL Algorithm (Example 1)



c. Finish the first pass by computing the maximum positive gain, G_m. Suggest how many swaps should be actually executed in the first pass.

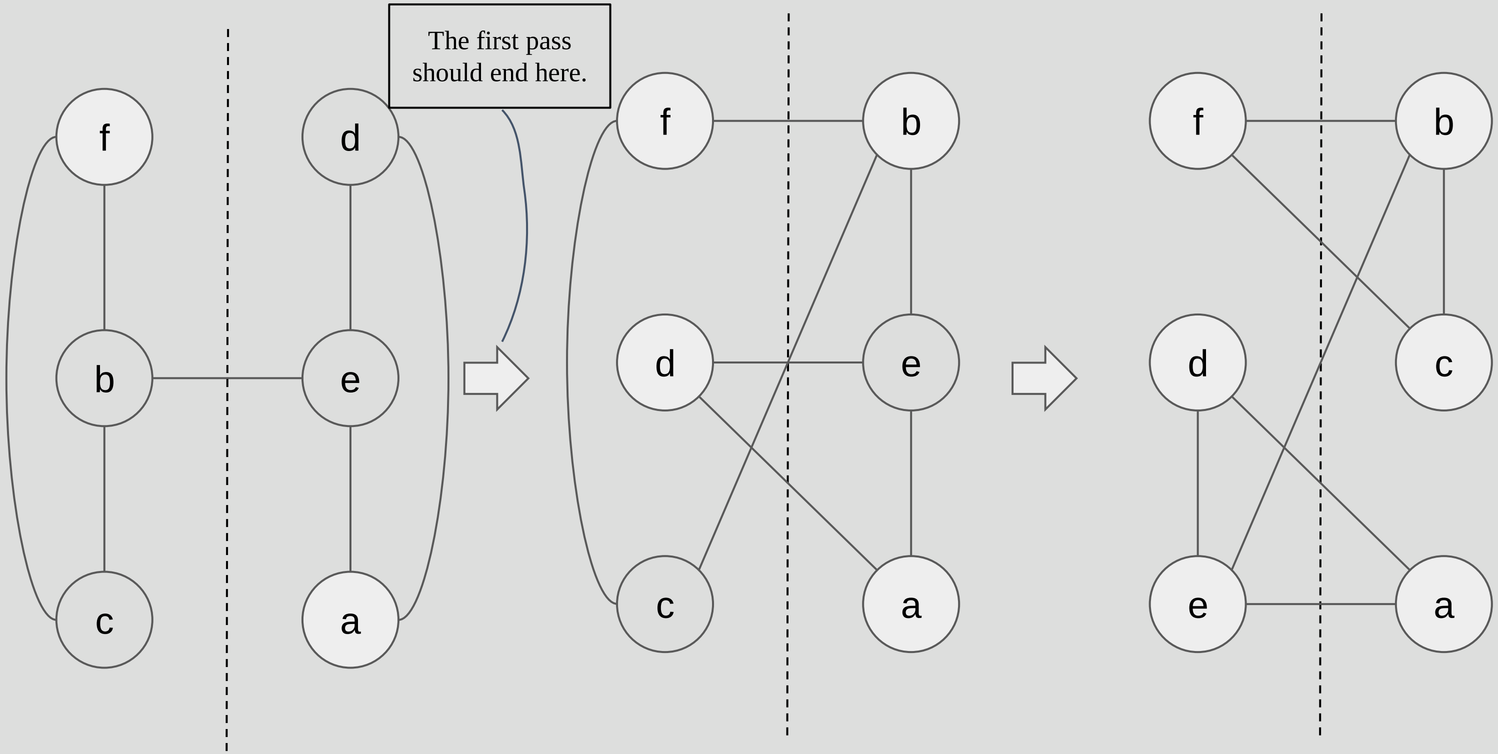
$G_1 = \Delta g_1 \quad = 4 \quad = 4$

$G_2 = \Delta g_1 + \Delta g_2 \quad = 4 - 3 \quad = 1$

$G_3 = \Delta g_1 + \Delta g_2 + \Delta g_3 = 4 - 3 \quad - 1 = 0$

Hence, maximum positive gain is achieved for m = 1. Only the swap for Δg_1, or (a, f) should be executed.

KL Algorithm (Example 1)



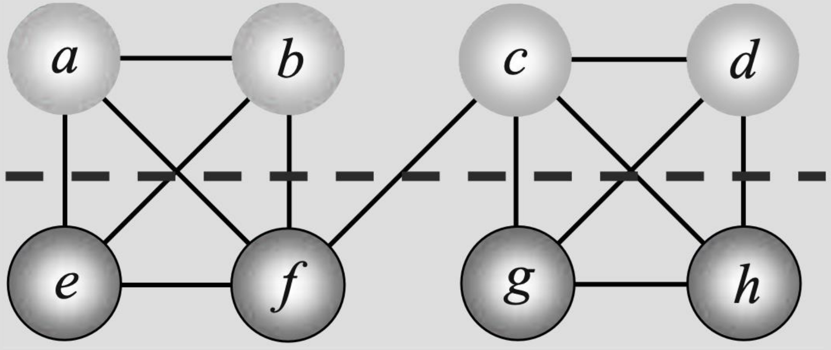
d. Should you perform subsequent passes of the algorithm? Why or why not?

Ans: Since $G_m > 0$, subsequent passes should be performed (until $G_m \leq 0$).

KL Algorithm (Example 2)

Given: initial partition of nodes *a*-*h* (right).

Task: perform the first pass of the KL algorithm.



Solution:

Initial cut cost = 9.

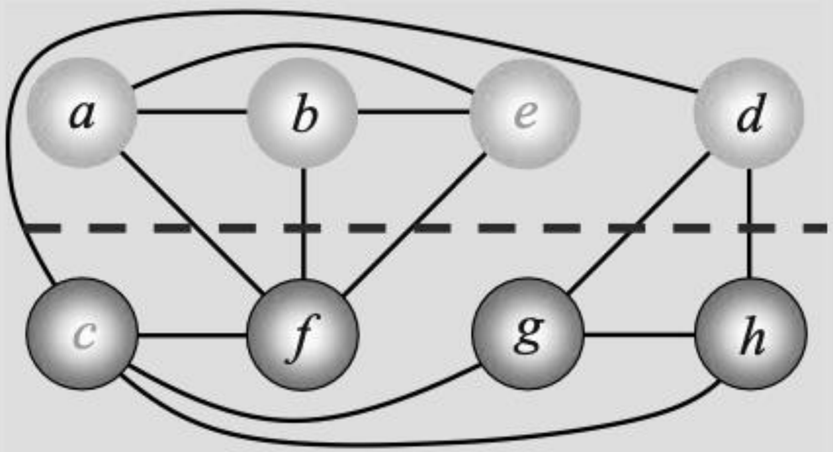
Compute $D(v)$ costs for all free nodes *a*-*h*.

$D(a) = 1$, $D(b) = 1$, $D(c) = 2$, $D(d) = 1$,

$D(e) = 1$, $D(f) = 2$, $D(g) = 1$, $D(h) = 1$

$\Delta g_1 = D(c) + D(e) - 2c(c,e) = 2 + 1 - 0 = 3$

Swap and fix nodes *c* and *e*.



Update $D(v)$ costs for all free nodes connected to newly swapped nodes *c* and *e*: *a*, *b*, *d*, *f*, *g* and *h*.

$D(a) = -1$, $D(b) = -1$, $D(d) = 3$,

$D(f) = 2$, $D(g) = -1$, $D(h) = -1$

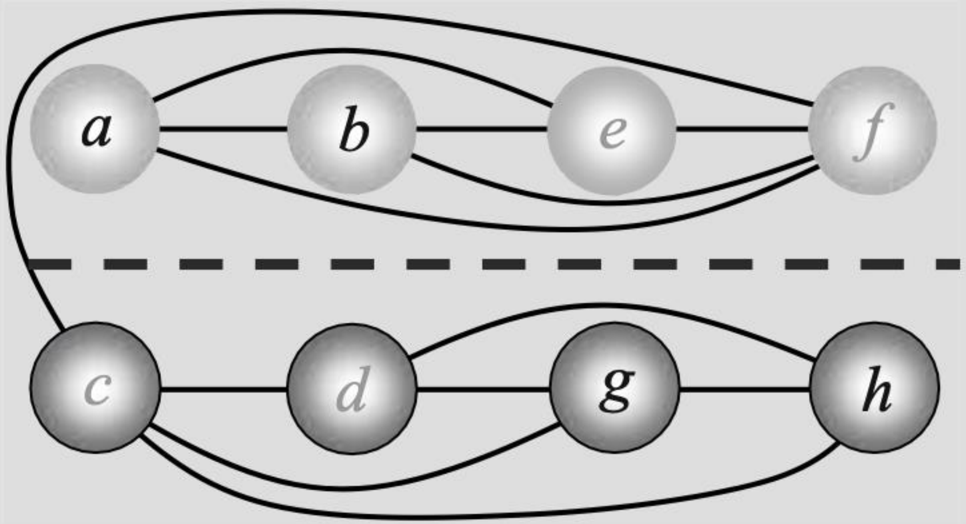
$\Delta g_2 = D(d) + D(f) - 2c(d,f) = 3 + 2 - 0 = 5$

Swap and fix nodes *d* and *f*.

KL Algorithm (Example 2)

Given: initial partition of nodes *a*-*h* (right).

Task: perform the first pass of the KL algorithm.

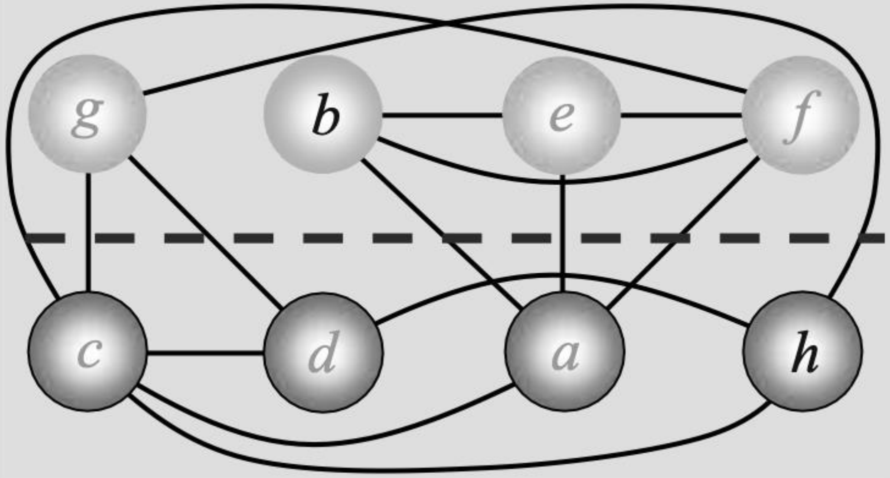


Update $D(v)$ costs for all free nodes connected to newly swapped nodes *d* and *f*: *a*, *b*, *g* and *h*.

$D(a) = -3$, $D(b) = -3$, $D(g) = -3$, $D(h) = -3$

$\Delta g_3 = D(a) + D(g) - 2c(a,g) = -3 + -3 - 0 = -6$

Swap and fix nodes *a* and *g*.



Update $D(v)$ costs for all free nodes connected to newly swapped nodes *a* and *g*: *b* and *h*.

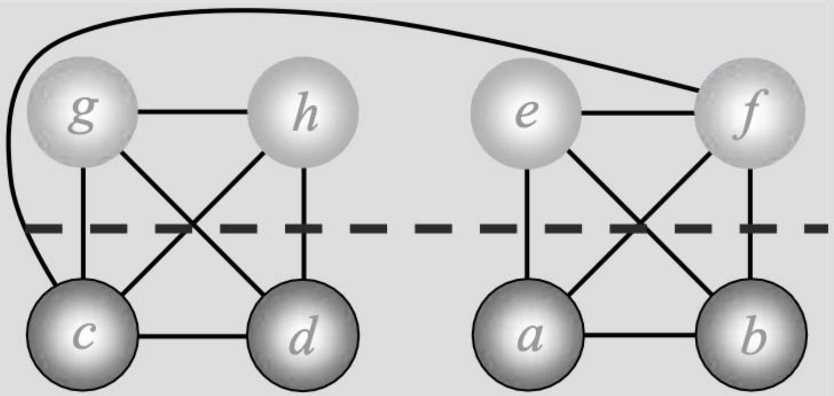
$D(b) = -1$, $D(h) = -1$

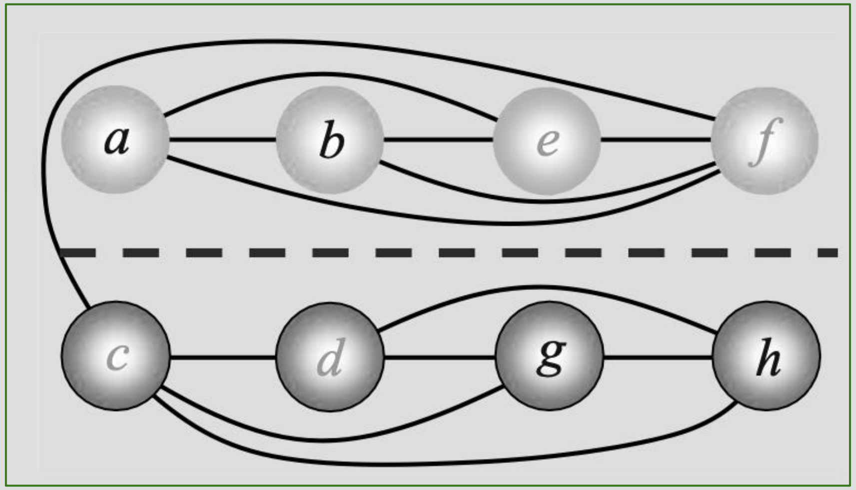
$\Delta g_4 = D(b) + D(h) - 2c(b,h) = -1 + -1 - 0 = -2$

Swap and fix nodes *b* and *h*.

KL Algorithm (Example 2)

Given: initial partition of nodes *a-h* (right).
Task: perform the first pass of the KL algorithm.





Compute maximum positive gain G_m.

$$G_1 = \Delta g_1 = 3$$
$$G_2 = \Delta g_1 + \Delta g_2 = 3 + 5 = 8$$
$$G_3 = \Delta g_1 + \Delta g_2 + \Delta g_3 = 3 + 5 + -6 = 2$$
$$G_4 = \Delta g_1 + \Delta g_2 + \Delta g_3 + \Delta g_4 = 3 + 5 + -6 + -2 = 0$$

$G_m = 8$ with $m = 2$. Since $G_m > 0$, the first $m = 2$ swaps are executed: (c,e) and (d,f). Additional passes are performed until $G_m \leq 0$.

Thank you.