

목차:

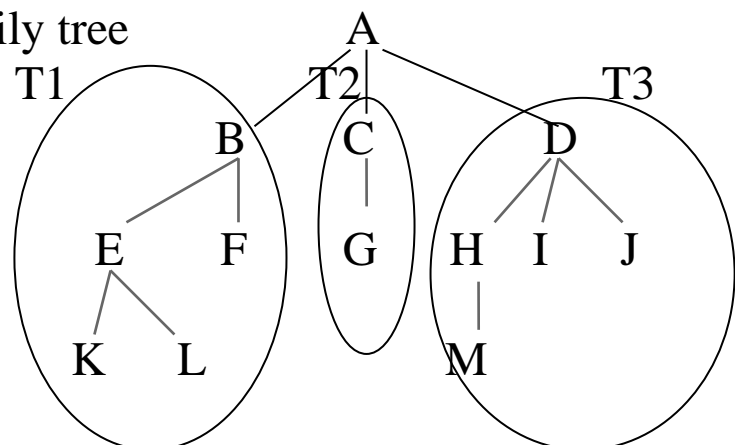
- 1) 트리 정의
- 2) 이진트리 (Binary Tree: BT) : definition and Representation
- 3) BT algorithm:
 - Traversing (Inorder, Preorder, Postorder)
 - Tree Build (exercise)
- 4) Threaded Tree: definition
- 5) HEAP (Maxheap, Min Heap)
- 6) Binary Search Tree (BST)
 - Insert, delete, search algorithm.

1. Tree Introduction

definition: A tree is finite set of one or more nodes

- 1) there is a special node called ROOT
- 2) the remaining nodes are partitioned into ($n \geq 0$ disjoint sets)
 T_1, \dots, T_n (subtrees of the root), where each of these sets is a tree

ex) family tree



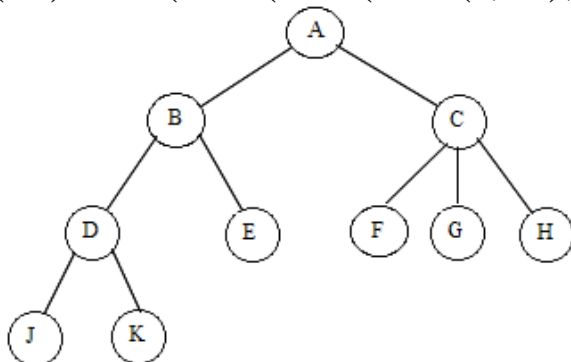
• Definitions/terminologies

- 1) **node** : item of information + branches to other nodes
- 2) **degree**: number of subtrees of a node
ex) degree of A = 3, C = 1, F = 0
- 3) **leaves**: nodes that have degree zero (leaf node, terminal node, K, L, F, G, M, I, J)
- 4) **children**: nodes that are directly accessible from a given node in the lower level (children of B \Rightarrow E, F)
- 5) **parent**: A node that has children (D is parent of H)
- 6) **siblings**: children of same parent
- 7) **grandparents, grandchildren**
(D is grandparent of M, A is grandparent of EFGHIJ)
- 8) **path**: a sequence from a node N_i to N_k
(ex, ABEL \rightarrow a path from A to L)
- 9) **ancestor**: all the nodes along the path from root to that node
(ancestor of M \rightarrow A, D, H)
- 10) **descendants**: all the nodes that are in its subtrees
(E, F, K, L are descendants of B)
- 11) **level**: let the root be at level 1
(if a node is at level I, then its children is level I+1)
- 12) **height or depth**: maximum level of any node in the tree
(ex. Depth of the figure is 4)

• Representation of Trees

- 1) **List representation** (트리의 표현)

(ex) (A (B (D (J, K), E), C (F, G, H)))



⇒ 임의의 노드는 varying number of fields, depending on the number of branches (예: 어떤 노드는 1 개의 child, 어떤 노드는 5 개의 child) So, the possible representation is:

data	link ₁	link ₂	link _n
------	-------------------	-------------------	-------	-------------------

2) Left Child-Right sibling representation

. Since it is easier to work with fixed size => require exactly two link or pointer fields per node

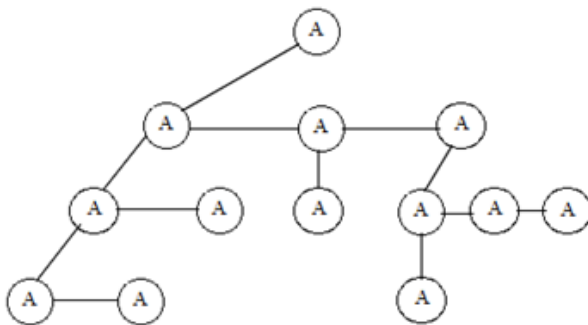
. condition:

every node has one leftmost child and right siblings
order of children in a tree is not important

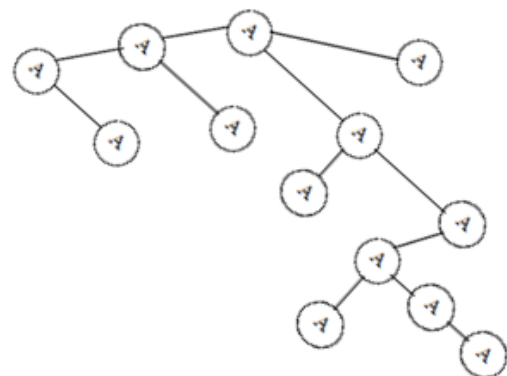
. data representation:

data	
left child	right siblings

. Left-child-right-sibling tree.



. Left child-right child tree



3) Representation As a Degree two tree

. to obtain degree two tree representation of a tree => rotate the left child-right-sibling tree clockwise by 45 degree

. This tree is also known as BINARY TREE

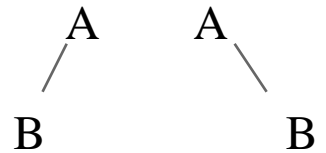
2. 이진 트리(Binary Tree: BT)

정의: consists of a **root** and two disjoint binary trees called the **left subtree** and the **right subtree**. (have a maximum of two children.)

- difference with tree

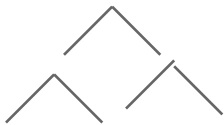
- 1) tree has no empty tree, but BT has empty
- 2) tree has no order, but BT has order

=> two different BT

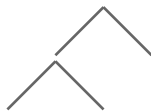


- Kinds of BT

- 1) Skewed BT: node 들이 한쪽으로 치우친 형태
- 2) Full BT: BT, in which all of the leaves are on the same level and every non-leaf node has two children
- 3) Complete BT: BT that is either full or full through the next to last level, with the leaves on the last level as far as to the left as possible



Full and complete



complete



not complete

- Properties of BT

we like to know maximum number of nodes in a BT of depth k ,

- 1) The maximum number of nodes on level i of a BT is $\Rightarrow 2^{i-1}, i \geq 1$
- 2) The maximum number of nodes in a BT of depth k is $\Rightarrow 2^k - 1, k \geq 1$

- Relation between number of leaf nodes and nodes of degree 2

“For any BT, T , if n_0 is the number of leaf nodes and n_2 is the number of nodes of degree 2, then $n_0 = n_2 + 1$ ”

(Proof) n_1 = number of nodes of degree 1.

n = total number of nodes, then

$$n = n_0 + n_1 + n_2$$

If B is the branches, then $n = B + 1$

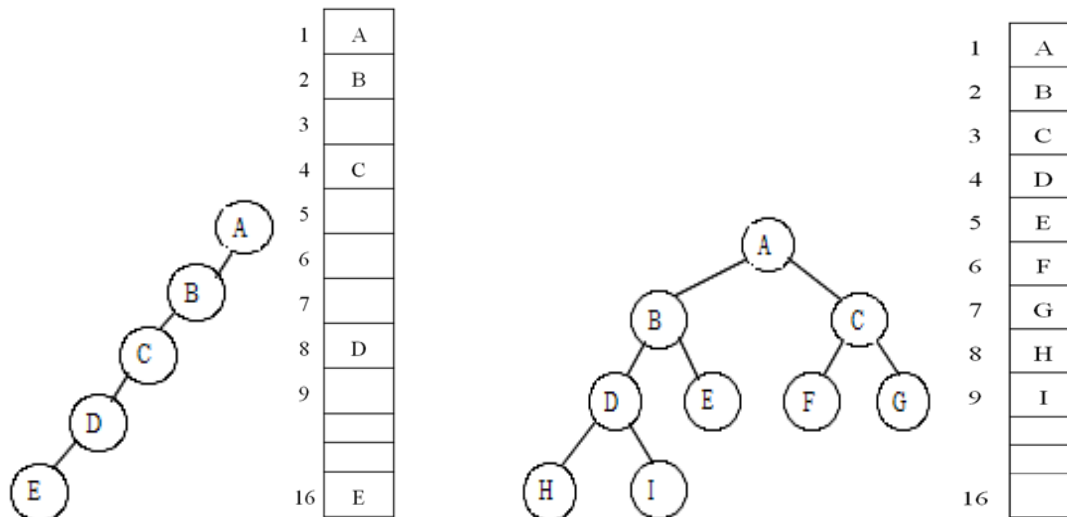
And all nodes stem from a node of degree one or two,

then $B = n_1 + 2n_2$ So, we obtain $n = (n_1 + 2n_2) + 1$,

$n_0 + n_1 + n_2 = n_1 + 2n_2 + 1$. Therefore, $n_0 = n_2 + 1$

• Binary Tree Representation

1) **Array Representation**: for any node with index i , $1 \leq i \leq n$



. parent(I) is at $(\lfloor i/2 \rfloor, \text{ if } i \neq 1)$,

. left-child(I) is at $(2i, \text{ if } 2i \leq n)$, If $2i > n$ then i has no left child

. right-child(I) is at $(2i+1, \text{ if } (2i+1) \leq n)$,

\Rightarrow If $(2i+1) > n$ then I has no right child

\Rightarrow for full binary tree, this representation is efficient

\Rightarrow But problem for skewed binary tree

Depth k 인 tree 에서 worst case 에는 $2^k - 1$ space 필요, 실제로는 k space 만 사용. \Rightarrow waste of a lot of space)

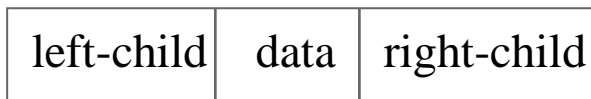
● Array representation:

- 1) waste of space (skewed tree 의 경우)
- 2) waste of time (Insertion & deletion requires movement of many nodes)

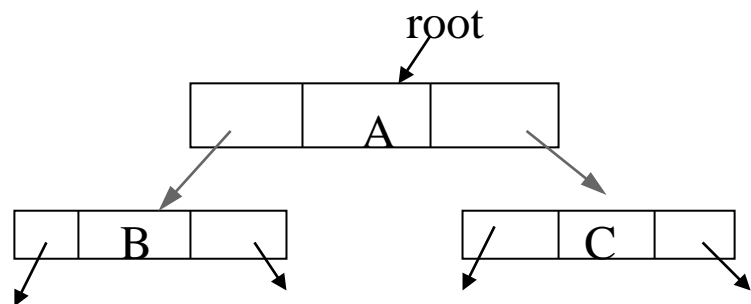
● Linked Representation

```
Typedef struct node *tree-pointer;
```

```
Typedef struct node {  
    int data;  
    struct node *left;  
    struct node *right;  
};
```



```
class Node {  
private:  
    int data;  
    Node *left;  
    Node *right;  
};
```



특성

- (1) array 로 표현하는 방법에 비해 메모리 절약 (필요한 node 의 숫자만큼의 memory 사용)
- (2) array 로 표현은 static (고정적)방법이고 linked list 표현방법은 dynamic 방법이다.
array 로 표현하면 고정된 메모리 사용하게 되나 linked list 로 표현하면 run-time 에 노드 생성 시 필요한 메모리를 확보하기 때문에 가변적(동적)이다.
- (3) insertion, deletion 이 빠르다(no data movement)

3. Binary Tree Traversal (이진 트리의 순회)

* traversing a tree: L- moving left, R- moving right, V- visit node

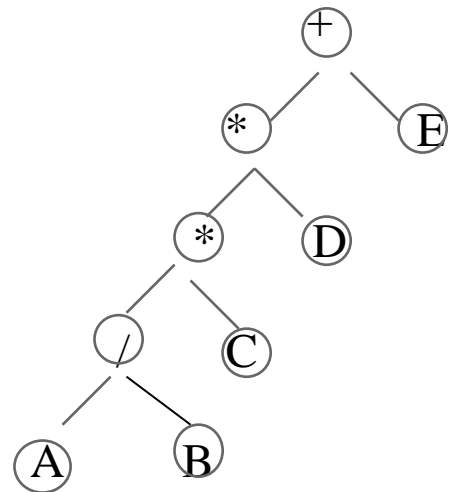
● Traversing method(순회 방법):

- 1) LPR(Inorder) : Visit left, Print current node, Visit right
- 2) LRP(Post order): Visit left, Visit right, print current node
- 3) PLR(Preorder): Print current node, visit left, visit right

* 산술식의 이진트리 표현 ($A / B * C * D + E$)

1) Inorder Traversal (LPR)

```
Void Tree::inorder(Node *ptr)
{
    if (ptr) {
        inorder(ptr->leftchild);
        cout << ptr->data;
        inorder(ptr->rightchild);
    }
}
```



1. 널 노드에 도달할 때까지 왼쪽 방향으로 이동
2. 널 노드에 도착하면 널 노드의 부모 방문
3. 순회는 오른쪽 방향으로 계속
4. 오른쪽으로 이동할 수 없을 때에는 바로 위 레벨의 방문하지 않은 노드에서 순회 계속

output : $A / B * C * D + E$

2) **PostOrder Traversal (LRP)**

```
void Tree::postorder(Node *ptr)
{
    if (ptr)
    {
        postorder(ptr->leftchild);
        postorder(ptr->rightchild);
        cout << ptr->data;
    }
}
```

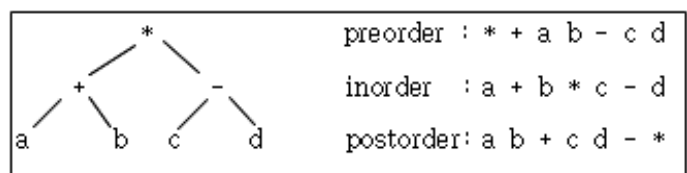
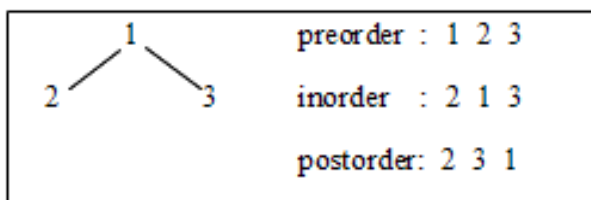
output: A B / C * D * E +

3) **Preorder Traversal**

```
void Tree::preorder(Node *ptr)
{
    if (ptr)
    {
        cout << ptr->data;
        preorder(ptr->leftchild);
        preorder(ptr->rightchild);
    }
}
```

output: + * * / A B C D E

ex)



Tree Build

*** Building tree for mathematical expression**

```
Struct node {  
    Char  data;      // one character input per node  
    Int   prio;      // priority number from precedence table  
    Struct node *left; // left  link  
    Struct node *right; // right link    }  
}
```

```
class Node {  
private:  
    int data;  Node *left;  Node *right;  
    Node(int value) {data = value; left = 0; right = 0;}  
friend class Tree;    };
```

```
class Tree {  
private:  
    Node *root;  
public:  
    Tree() {root = 0;}  
    ~Tree();  
    .....    };
```

*** Precedence Table**

```
char prec[5][2] = {'^' 3,  '*', 2,  '/', 2,  '+', 1,  '-', 1};
```

'^'	'*'	'/'	'+'	'-'
3	2	2	1	1

-Get expression: gets math expressions from KBD (ex. 8+9-2*3)

- Build Tree

```
while (input !=NULL)  
{    . create new-node  
    . assign DATA-INPUT into new-node's data field & default prio '4'  
    . for i=0 to 4  (if new-node -> data == prec[i][0])  
        then new-node ->prio = prec[i][1]
```

```

. if (i==5)  then  call Operand(new-node)
              else  call operator(new-node)    }  }

```

*** Operand(new-node)**

```

If  HEAD==NULL  then  HEAD=new-node  return
P = Head
While (p->right !=NULL)  p=p->right
P->right = new-node

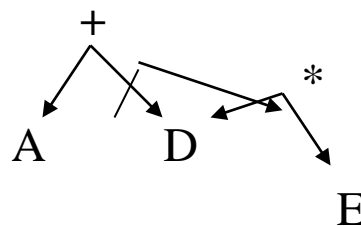
```

*** Operator (new-node)**

```

if (head->prio ≥ new-node->prio)
    new-node->left = Head
    Head = new-node

```



```

Else
    New-node->left = Head->right
    Head -> right = new-node

```

*** Tree Evaluation**

```

evalTree (p)  {
    if  p!=NULL  {
        if p->data in [0..9]  then  value = p->data-'0'
        else
            left = evalTree(p->left)
            right=evalTree(p->right)
            switch (p->data)
                case '+':  value=left+right;
                case '-':  value=left-right;
                case '*':  value=left*right;
                case '/':  value=left/right;
            }endif
        }else  "Empty tree" }
    Return value

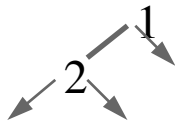
```

4. 스레드(threaded) 이진 트리

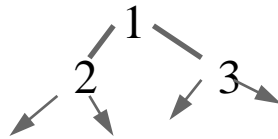
정의: 스레드(Thread): [A.J. Perlis & C. Thornton]

=> null link를 다른 node를 가리키는 pointer로 변환한 것을 thread 라 하며 inorder 순회에 효과적으로 사용할 수 있다.

- Binary tree has: total $2n$ links, (그중 $n+1$ null links (or empty subtrees))
=> more null links than actual pointers



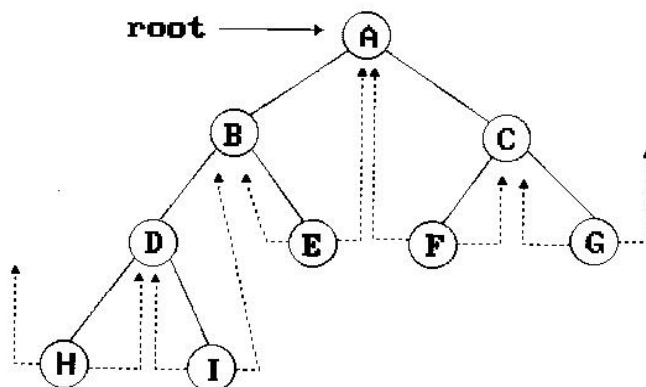
[$n \rightarrow 2$, Null $\rightarrow 3$]



[$n=3$, null link=4]

- Threads 연결 규칙 (PTR 이 현재노드라 가정하면)

- 1) If $\text{ptr} \rightarrow \text{left}$ is null : ptr 의 inorder predecessor 를 가리키게 함. 즉, inorder 순회시 ptr 앞에 방문하는 노드를 가리키게 함
- 2) If $\text{ptr} \rightarrow \text{right}$ is NULL : ptr 의 inorder successor 를 가리키게 함. 즉, inorder 순회시 ptr 의 다음에 오는 node 를 가리키게 함.

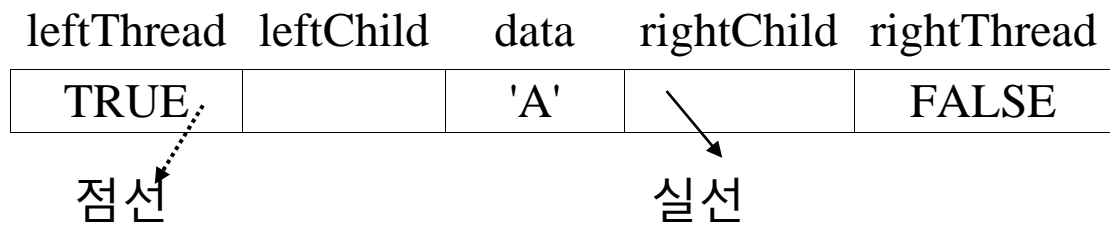


- . E 의 leftchild is null : E 의 left 는 inorder predecessor B 에 연결
- . E 의 rightchild is null: E 의 right 는 inorder successor A 에 연결

● Representation of Threaded Tree

```

Struct Node{
    int    left_thread;
    Node   *left-child;
    char   data;
    Node   *right-child;
    int    right_thread;
}
    
```



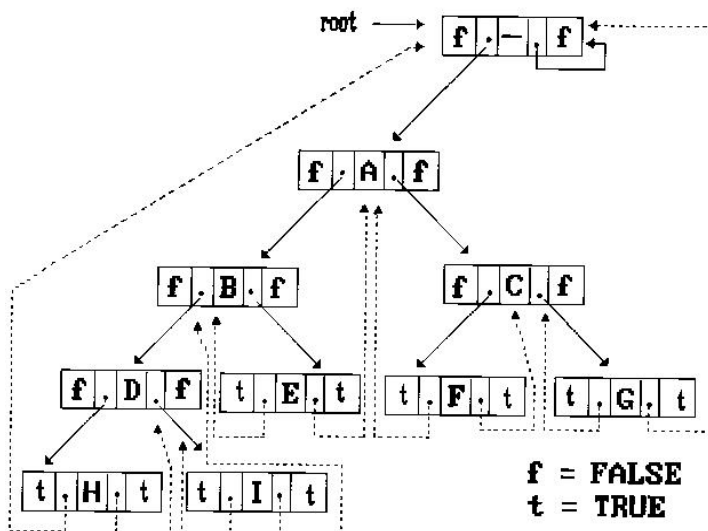
thread 는 점선으로 표기, normal pointer 는 실선으로 표기

if thread field == true then contains a thread

if thread field == false then contains a pointer to a child

* 문제는 2 개의 thread 가 dangling 되어 있다는 점이다.

- (1) H 의 inorder predecessor 가 없음 (H 가 inorder 의 맨 처음 node 임)
- (2) G 의 inorder successor 가 없음 (G 가 inorder 의 맨 나중 node 임)
- (3) head node 를 만들어 연결시킴으로 해결하며 그 결과는 아래 그림임



- 활용: inorder traversal 에 활용함

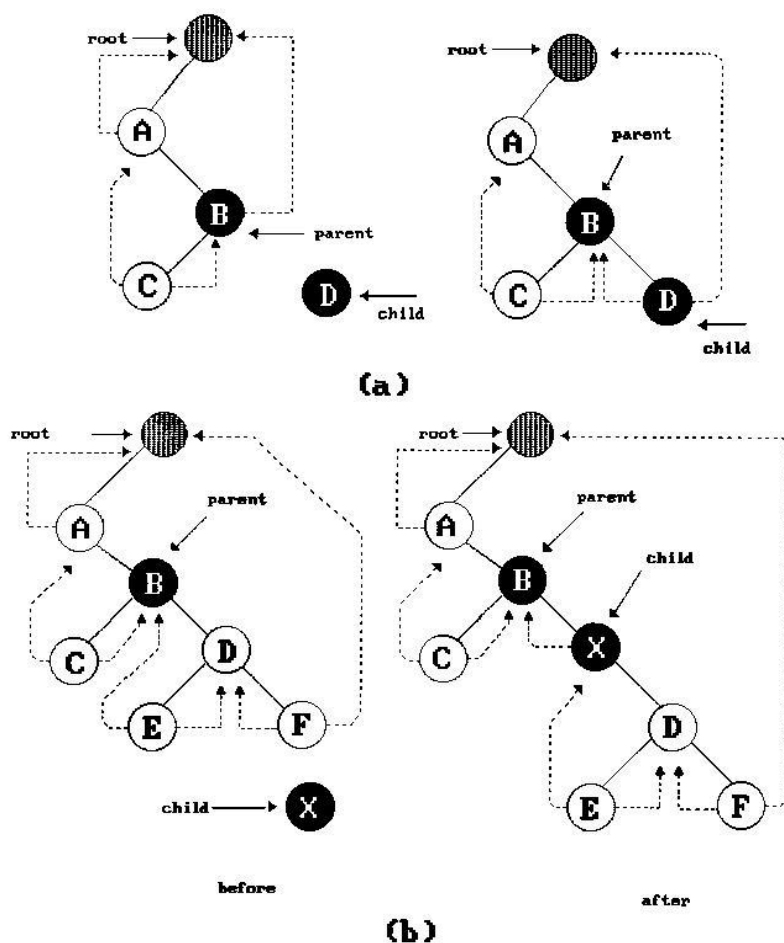
recursive inorder traversal 을 간단한 non-recursive version 으로 구현할 수 있다.

computing time은 마찬가지로 $O(n)$ 이지만 recursive call 에 따른 overhead는 없어짐

- Inorder: H D I B E A F C G

- 예) 1) Node E 의 right_thread is TRUE, successor of E is \Rightarrow A
 2) Node A 의 right_thread is False, C 부터 시작하여,
 C 의 leftchild link 를 따라서 F 까지간다. \Rightarrow F is A 의 후속자

예)



5. HEAP

정의: HEAP is a special form of FULL binary tree that is used in many applications

- 1) MAX TREE: is a tree in which the key value in each node is larger than the key values in its children (if any).

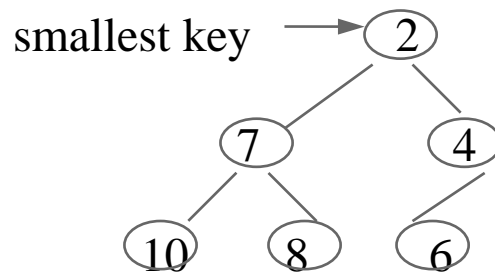
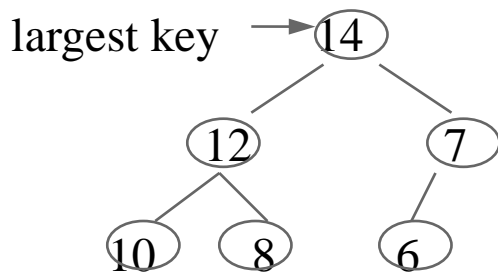
MAX HEAP => is a complete binary tree that is also a max tree

- 2) MIN TREE: is a tree in which the key value in each node is smaller than the key values in its children (if any).

MIN HEAP => is a complete binary tree that is also a min tree

ex) MAX HEAPS

MIN HEAPS



- Representation - Use Arrays, (same as tree for array representation scheme)

- *MaxHeap ADT*

structure *MaxHeap*

objects : 각 노드의 값이 그 자식들의 것보다 작지 않도록
조직된 $n > 0$ 원소의 완전 이진 트리

functions :

$\forall \text{ heap} \in \text{MaxHeap}, \text{ item} \in \text{Element}, \text{ n}, \text{ max_size} \in \text{integer}$

MaxHeap Create(max_size) ::= 최대 max_size개의 원소를 가질 수
있는 공백 Heap 생성

Boolean HeapFull(heap, n) ::= if (n == max_size) return TRUE
else return FALSE

MaxHeap Insert(heap, item, n) ::= if (!HeapFull(heap, n)) item을 heap에
삽입하고 그 heap을 반환 else return 에러

Boolean HeapEmpty(heap, n) ::= if (n == 0) return TRUE
else return FALSE

Element Delete(heap, n) ::= if (!HeapEmpty(heap, n))
Heap에서 가장 큰 원소를 제거하고 그 원소를 반환 else
return 에러

#define MAX_ELEMENTS 200 /* 최대 heap 크기 + 1 */
#define HEAP_FULL(n) (n == MAX_ELEMENTS-1)
#define HEAP_EMPTY(n) (!n)

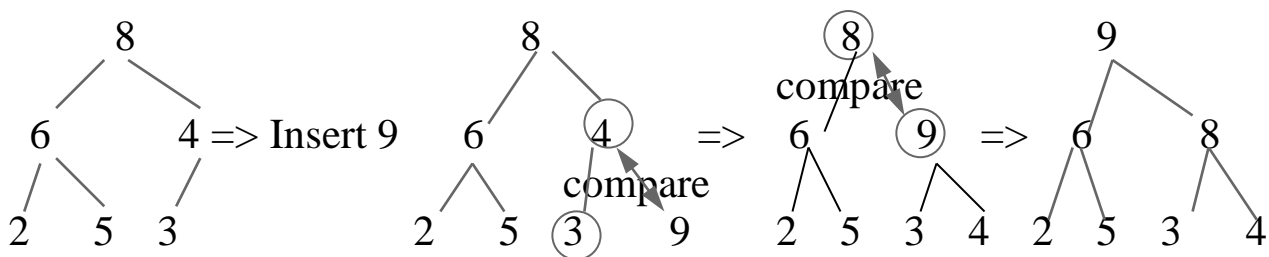
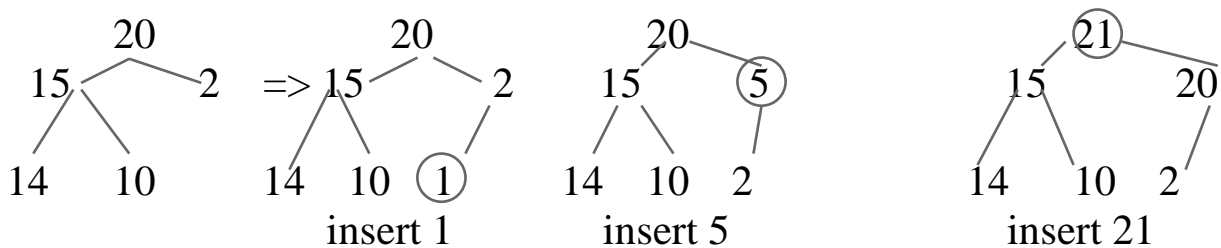
typedef struct {
 int key;
 /* 다른 필드들 */
} element;
element heap[MAX_ELEMENTS];
int n = 0;

● PRIORITY QUEUE

. HEAPs are used to implement PRIORITY QUEUE

- ⇒ the element to be deleted is the one with **highest(lowest) priority**
- ⇒ For example, Job scheduler use the priority with the **shortest run time**, implement the priority queue that holds the jobs as a **min heap**
- ⇒ MAX(MIN) HEAP may be used
- ⇒ **ARRAY** is a simple representation of a priority queue (easily add to P.Q. by placing the new item at the current end of array)
⇒ insertion complexity $O(1)$

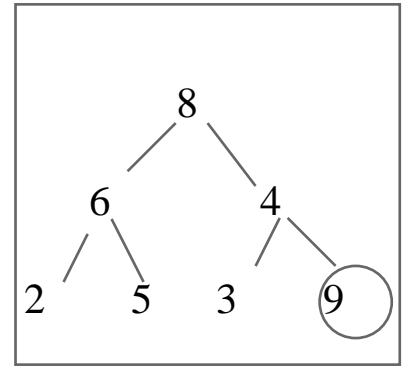
● Insertion into a MAX HEAP




```

void insert_maxheap (element item, int *n)
{
    int i
    if (HEAP_FULL(*n)) {
        printf("Heap is full...\n"); exit(1);
    }
    I = ++(*n);
    while ((I!=1) && (item > heap[i/2]    ))
    {
        heap[I] = heap[i/2];
        I =  $\lfloor i/2 \rfloor$ ;
    }
    Heap.[I] = item;
}

```



1	2	3	4	5	6	7
8	6	4	2	5	3	9

for $I = 7$,
 since $(\text{item} = 9) > (\text{heap}[7/2] = 4)$, \Rightarrow $(\text{heap}[7] = \text{heap}[3])$

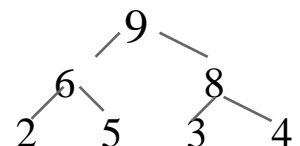
1	2	3	4	5	6	7
8	6	4	2	5	3	4

for $I = i/2 = 3$,
 since $(9 > \text{heap}[3/2] = 8)$ \Rightarrow $(\text{heap}[3] = \text{heap}[1])$

1	2	3	4	5	6	7
8	6	8	2	5	3	4

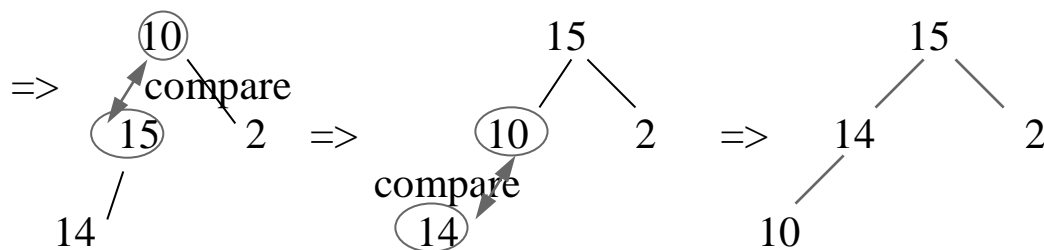
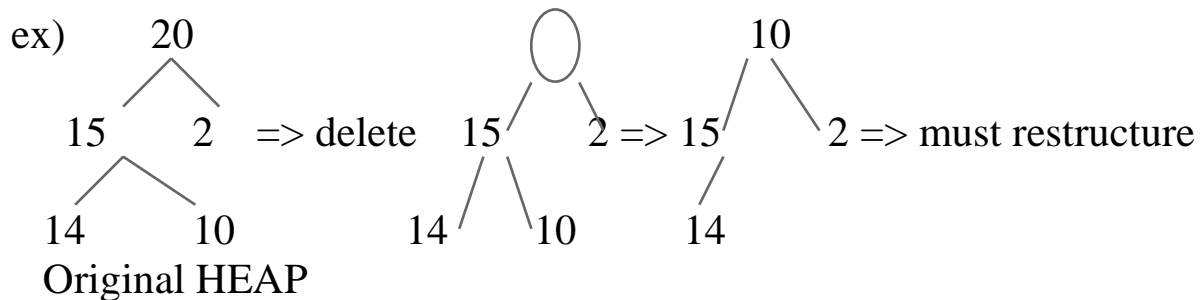
$i/2 = 1$, so exit while loop
 $\text{heap}[1] = \text{item} \Rightarrow (\text{heap}[1] = 9)$

1	2	3	4	5	6	7
9	6	8	2	5	3	4



● Deletion from a MAX HEAP

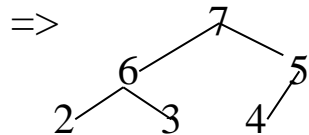
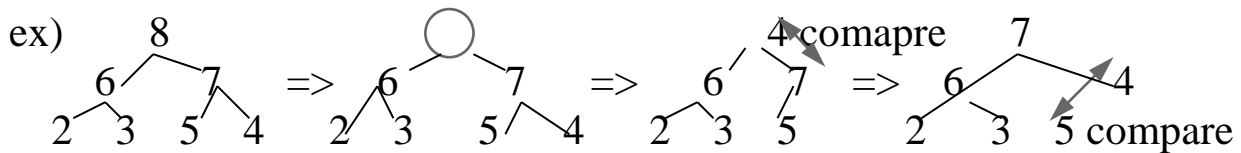
- . Always take it from the ROOT of the HEAP. => must restructure the HEAP (complexity is $O(\log n)$)



element delete-maxheap (int *n)

```
{  int parent, child;
    element item, temp;
    .....
    item = heap[1];          /* save the highest key*/
    temp = heap[(*n) - 1];   /* use the last element */
    parent = 1;
    child = 2;

    while (child <= *n) {
        if (child < *n) && (heap[child] < heap[child+1])
            child++;          /* find largest child */
        if (temp >= heap[child]) break;
        heap[parent] = heap[child];
        parent = child;
        child = child * 2;
    }
    heap[parent] = temp;
    return item; }
```



1	2	3	4	5	6	7
8	6	7	2	3	5	4

1) $n = 7$, item = 8, temp = 4, $n = 6$, child=2, parent =1

2) While (child <= 6)

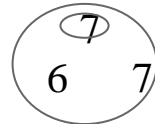
. child <6, && heap[child]=6 < heap[child+1]=7)

=> **child=3**

. temp(=4) < (heap[child]=7)

. **heap[1] = 7**

.parent = 3, child = 6



1	2	3	4	5	6
7	6	7	2	3	5

3) while (child <= 6)

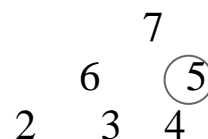
. child <6 && (heap[child] = 5 > heap[child+1]=4)=>child=6

. temp(=4) < heap[child] = 5

. **heap[3]=5** (heap[parent] = heap[child])

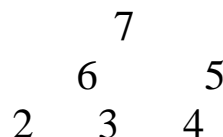
. child = 12, parent = 6 => **exit while loop**

1	2	3	4	5	6
7	6	5	2	3	5



4) heap [6] = temp (4)

1	2	3	4	5	6
7	6	5	2	3	4



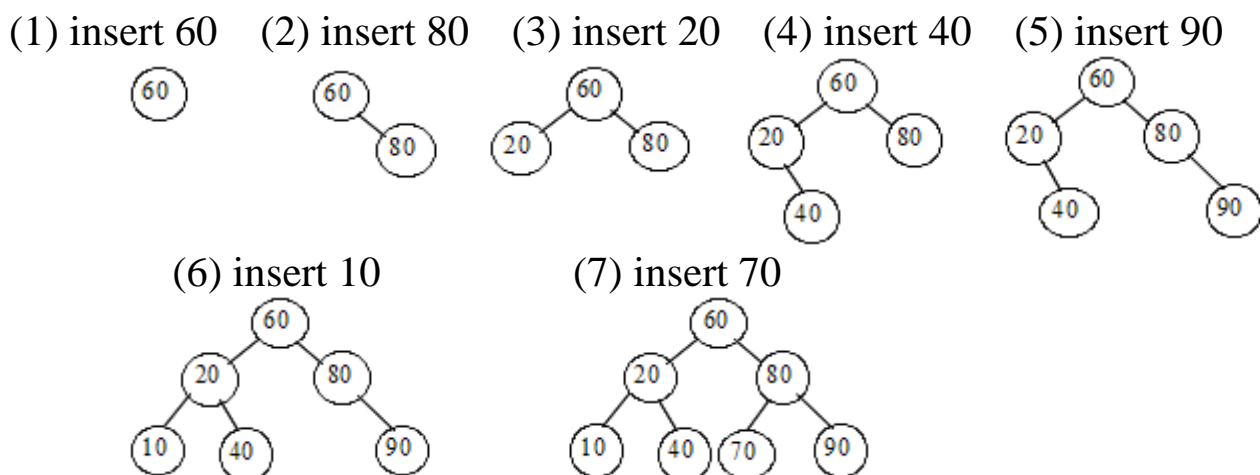
6. Binary Search Trees (BST)

- ⇒ HEAP is suitable for **priority queue** applications, but it's not well suited if we want to delete **arbitrary elements**.
- ⇒ BST performs better than any data structure when we wish to perform INSERTION, DELETION, SEARCHING => BST can perform these operations by both KEY VALUE (예: delete element x), and BY RANK (예: delete 6th position)

Definition: BST is a binary tree. It may be empty, if not, it satisfies the followings;

- 1) Every element has a key, and Keys are unique
- 2) The keys in leftsubtree must be smaller than the keys in ROOT of subtree
- 3) The keys in rightsubtree must be larger than the keys in ROOT of subtree

[예제#1] 60 80 20 40 90 10 70 순서로 삽입



- Representation : same as Binary Tree representation
- Tree operation: same as tree traversal (inorder, preorder, postorder)
+ Additional operations (insertion, deletion, search)

1) Searching a BST

search (ptr, int key)

```
{
    if (ptr == NULL)    return NULL;    //search unsuccessful
    else {
        if (key == p->data)    return ptr;
        else if (key < ptr->data)
            ptr = search(ptr->left, key);    //search leftsubtree
        else if (key > ptr->data)
            ptr= search(ptr->right, key); //search rightsubtree
    }
    return ptr;
}
```

2) Inserting into a BST

* In order to insert, we must search the tree => if the search is unsuccessful, we insert the element at the point the search terminated

INSERT (ptr, key) //recursive version

```
{
    if (ptr=NULL) {
        create new_node(ptr);
        ptr->data = key;
        ptr->left = NULL;
        ptr->right = NULL;
    }
    else if (key < ptr->data)
        ptr->left = INSERT(ptr->left, key);
    elseif (key > ptr->data)
        ptr->right = INSERT(ptr->right, key);
    return ptr;
}
```

3) DELETE (3 cases)

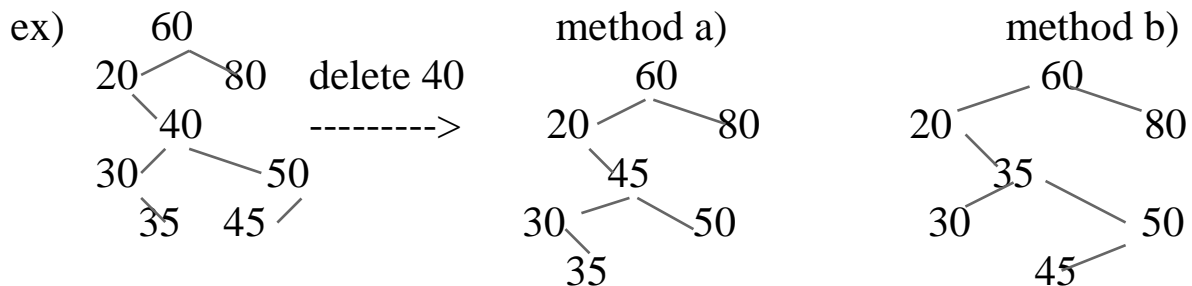
* Leaf node => set the child field of the node's parent pointer to NULL and free the node

* Nonleaf node with one child => change pointer from parent to single child



* Nonleaf node with two children

- replace with smallest element in rightsubtree
- replace with largest element in leftsubtree



```
delete (ptr, key) {
  if (ptr != NULL) {
    if (key < ptr->data)
      ptr->left = delete(key, ptr->left)    /* move to the node */
    else if (key > ptr->data)
      ptr->right = delete(key, ptr->right) /* arrived at the node*/
    else if ((ptr->left == NULL) && (ptr->right == NULL))
      ptr = NULL                          /*leaf*/
    else if (ptr->left == NULL) {
      p = ptr; ptr = ptr->right; delete(p); /*rightchild only*/ }
    elseif (ptr->right == NULL) {
      p = ptr; ptr = ptr->left; delete(p); /*left child only */ }
    else temp = find_min(ptr->right) /*both child exists */
      ptr->data = temp->data;
      ptr->right = delete(ptr->right, ptr->data);
  }
}
```

```

Else    printf("Not found");

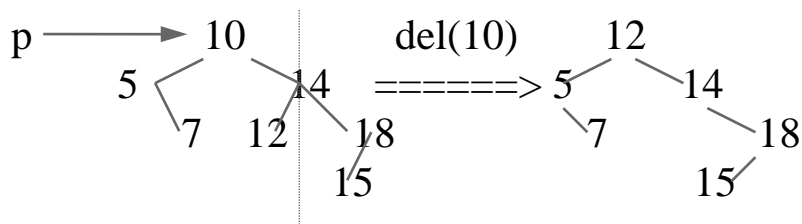
return ptr;
}

```

```

int find_min(p)    /*right subtree 에서 가장 작은것 선택 */
{
    if (p->left ==NULL)
    {
        return p;
    }
    else
        find_min(p->left);
}

```



- 선언

```

class Node {
    .....
};

class Tree {
private:
    Node *root;
public:
    Tree() {root = 0;}
    ~Tree();
    void insertTree(int);
    void deleteTree(int);
    Node *deleteBSTree(Node *, int);
}

```

```

void searchTree(int);
Node *searchBSTree(Node *, int key);
void traverseTree();
void inorderTraverse(Node *);
void drawTree();
void drawBSTree(Node *, int);
Node *findmin(Node *p);
int tree_empty();
void freeBSTree(Node *);
};

```

```

Tree::~~Tree()    {   freeBSTree(root);   }

```

```

void Tree::drawTree() {   drawBSTree(root, 1);   }

```

```

void Tree::drawBSTree(Node *p, int level) {
    if (p != 0 && level <= 7) {
        drawBSTree(p->right, level+1);
        for (int i = 1; i <= (level-1); i++)
            cout << " ";
        cout << p->data;
        if (p->left != 0 && p->right != 0)    cout << " <" << endl;
        else if (p->right != 0)              cout << " /" << endl;
        else if (p->left != 0)               cout << " \\" << endl;
        else                                cout << endl;
        drawBSTree(p->left, level+1);
    }
}

```