

6. Data Structures

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<https://cister-labs.github.io/alg2324>



CISTER - Research Centre in
Real-Time & Embedded
Computing Systems

- Sets and Sequences
- Buffers:
 - Stacks
 - Queues
 - Priority queues
- Dictionaries
 - Hashtables
 - Search trees

We have seen that

Different **data structures** are better at different **operations**

We will see

Useful data structures and associated operations (code)

Examples

Arrays can have operations to implement sets, multisets, trees, etc.

Sets and Sequences

```
#define MAXS 100  
typedef int SetInt [MAXS] ;
```

Given SetInt s:

$5 \in s \Leftrightarrow s[5] \neq 0$

```
#define MAXMS 100  
typedef int MSetInt [MAXS] ;
```

Given MSetInt ms:

$\{4, 4\} \subseteq ms \Leftrightarrow ms[4] \leq 2$

Sets and Multisets – operations

```
void initSet      (SetInt);  
int  searchSet   (SetInt, int);  
int  addSet      (SetInt, int);  
int  emptySet    (SetInt);  
void unionSet    (SetInt, SetInt,  
                 SetInt);  
void intersectSet (SetInt, SetInt,  
                 SetInt);  
void differenceSet (SetInt, SetInt,  
                 SetInt);
```

```
void initMSet     (MSetInt);  
int  searchMSet   (MSetInt, int);  
int  addMSet      (MSetInt, int);  
int  emptyMSet    (MSetInt);  
void unionMSet    (MSetInt, MSetInt,  
                 SetInt);  
void intersectMSet (MSetInt, MSetInt,  
                 MSetInt);  
void differenceMSet (MSetInt, MSetInt,  
                 MSetInt);
```

Ex. 6.1: What is the expected cost of each function? Could you implement them?

Sequences – Recall linked lists

```
typedef struct list { int value ;  
struct list *next;  
} *LInt;
```

```
LInt add (int x, LInt l) {  
    LInt new =  
        malloc(sizeof(struct list));  
    if (new != NULL) {  
        new->value=x;  
        new->next=l ;  
    }  
    return new;  
}
```

```
LInt dda (int x, LInt l) {  
    LInt pt = l;  
    while (pt != NULL) pt = pt->next;  
    pt = malloc(sizeof(struct list));  
    pt -> value = x;  
    pt -> next = NULL ;  
    return l ;  
}
```

Sequences – Recall linked lists (fixed)

```
typedef struct list {  
    int value ;  
    struct list *next;  
} *LInt;
```

```
LInt add (int x, LInt l) {  
    LInt new = malloc(sizeof(struct  
        list ));  
    if (new != NULL) {  
        new->value=x;  
        new->next=l ;  
    }  
    return new;  
}
```

```
LInt dda (int x, LInt l) {  
    LInt pt = l, prev;  
    while (pt != NULL) {  
        prev = pt; pt = pt->next; }  
    pt = malloc(sizeof(struct list));  
    pt->value = x;  
    pt->next = NULL ;  
    if (l==NULL) l = pt;  
    else prev->next = pt;  
    return l;  
}
```

Ex. 6.2: What is the possible complexity of lookup, concat, reverse?

Sequences – reverse analysis

```
LInt reverse1 (LInt l) {
    LInt r, pt;
    if (l==NULL || l->next==NULL)
        r=l;
    else {
        r = pt = reverse1 (l->next);
        while (pt->next != NULL)
            pt = pt->next;
        pt->next = l;
        l->next = NULL;
    }
    return r; }
```

```
LInt reverse2 (LInt l) {
    LInt r, tmp;
    r = NULL;
    while (l !=NULL) {
        tmp=l; l=l->next;
        tmp->next=r; r=tmp;
    }
    return r;
}
```

Ex. 6.3: What is the complexity of each reverse?

Ex. 6.4: What is the (informal) loop invariant in reverse2, assuming:
pre: $l==l_0$ and post: $r==rev(l_0)$?

```
https://docs.scala-lang.org/  
overviews/collections-2.13/  
performance-characteristics.html
```

Buffers (stacks and queueus)

```
#define MAX 1000
typedef struct stack {
    int values [MAX];
    int sp;
} Stack;
```

```
typedef struct cell {
    int value;
    struct cell *next;
} Cell , *Stack;
```

```
typedef struct stack {
    int size;
    int *values;
    int sp;
} Stack;
```

```
#define MAX 1000
typedef struct stack {
    int values [MAX];
    int sp;
} Stack;
```

with static arrays

```
typedef struct cell {
    int value;
    struct cell *next;
} Cell , *Stack;
```

with linked lists

```
typedef struct stack {
    int size;
    int *values;
    int sp;
} Stack;
```

with dynamic arrays

Ex. 6.5: (Informally) what is the expected complexity of: push, pop, head?

Exercise: Push-pop with dynamic arrays

```
void push (Stack *s , int x){
    if (s->sp == s->size)
        doubleArray (s);
    s->values[s->sp++] = x;
}

void doubleArray (Stack *s){
    s->size *= 2;
    s->values =
        realloc(s->values, s->size);
}
```

```
int pop (Stack *s){
    // reduces by half when only
    // 25% capacity is used
    ...
}

void halfArray (Stack *s){
    ...
}
```

Ex. 6.6: Implement the optimised pop function and discuss its complexity.

```
#define MAX 1000
typedef struct queue
{
    int values [MAX];
    int start, size;
} Queue;
```

```
typedef struct cell {
    int value ;
    struct cell *prox ;
} Cell ;

typedef struct queue {
    struct cell *start, *end;
} Queue;
```

```
typedef struct queue
{
    int max;
    int *values;
    int start, size;
} Queue;
```

Queues

```
#define MAX 1000
typedef struct queue
{
    int values [MAX];
    int start, size;
} Queue;
```

with static arrays
(circular)

```
typedef struct cell {
    int value ;
    struct cell *prox ;
} Cell ;

typedef struct queue {
    struct cell *start, *end;
} Queue;
```

with linked lists

```
typedef struct queue
{
    int max;
    int *values;
    int start, size;
} Queue;
```

with dynamic arrays
(circular)

Ex. 6.7: (Informally) what is the complexity of: `init`, `isEmpty`, `enqueue`, `dequeue`?

- Binary tree
- Each node is smaller than any of its children
- Implemented as an array

```
#define MAX 1000
typedef struct prQueue {
    int values [MAX];
    int size ;
} PriorityQ ;
```

Tree example in the board

```
size=17  0  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16
values:  [10 15 11 16 22 35 20 21 23 34 37 80 43 22 25 24 28]
```

Ex. 6.8: Using the previous example, provide an expression to:

1. calculate the index of the *left* tree given a position i
2. calculate the index of the *right* tree given a position i
3. calculate the index of the *parent* of a given a position i
4. calculate the index of the index of the *first leaf*

Ex. 6.9: Define `bubbleUp(int i, int h[])`

Fixes a min-heap by swapping the i -th element with the parent while needed.

Ex. 6.10: Define `bubbleDown(int i, int h[], int N)`

Fixes a min-heap by swapping the i -th element with one of the children while needed.

Ex. 6.11: Define the following operations:

- void empty (PriorityQueue *q) – initialises the queue;
- int isEmpty (PriorityQueue *q) – tests if q is empty;
- int add (int x, PriorityQueue *q) – adds a value x, returning 0 when the queue is full;
- int remove (PriorityQueue *q, int *rem) – removes the next element, and copies it to *rem*.

Dictionarys

Dictionary: maps **keys** to **values**

(Keys are unique)

Idea

- **Magic function hash** converts a key into an **index** (number).
- This **index** points to the position of an array where the value *should* be found.
- Usually the size of the array is **less** than the set of possible keys, i.e., **hash is not injective**.
- If 2 keys have the same **hash** value, there is a **colision** that must be mitigated (alternative solutions exist).

Hashtables: Closed and Open Addressing

Closed Addressing (or chaining)

- Table = *array of linked lists*
- Find value of key k :
 - go to index $\text{hash}(k)$
 - traverse list until k

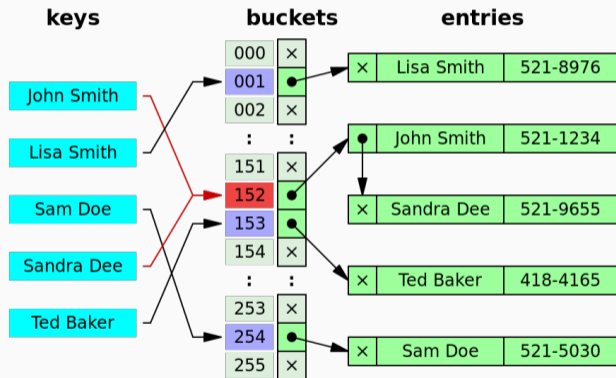
Open Addressing

- Table = *just an array*
- Find value of key k :
 - go to index $\text{hash}(k)$
 - "*jump*" until k

Some concerns

- Use dynamic arrays (grow when the **load factor** ($\#keys/H\text{SIZE}$) gets high)
 - Need to *rehash*
- Smart *jumps* (probe function to know where to jump)
- Need to *garbage collect* in open addressing

Intuition: Hashtables with Closed Addressing



(from Wikipedia)

Hashtables with Closed Addressing

- `int hash(int k, int size);`
- `void initTab(HTChain h);`
- `int lookup(HTChain h, int k, int *i);`
- `int update(HTChain h, int k, int i);`
- `int remove(HTChain h, int k);`

```
#define HSIZE 1000

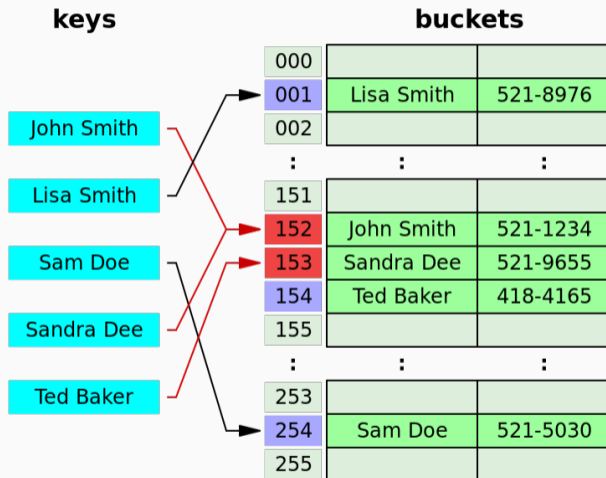
typedef struct bucket {
    int key;
    int info;
    struct bucket *next;
} *Bucket;

typedef Bucket
    HTChain[HSIZE];
```

Ex. 6.12: Implement lookup

Ex. 6.13: (Informally) what is the expected complexity of each function?

Intuition: Hashtables with Open Addressing



(from Wikipedia)

Hashtables with Open Addressing

- `int hash(int k, int size);`
- `void initTab(HashTable h);`
- `void lookup(HashTable h, int k, int *i);`
- `void update(HashTable h, int k, int i);`
- `void remove(HashTable h, int k);`
- `int find_probe (HashTable h, int k)`
 - linear vs. quadratic probing (why quadratic?)

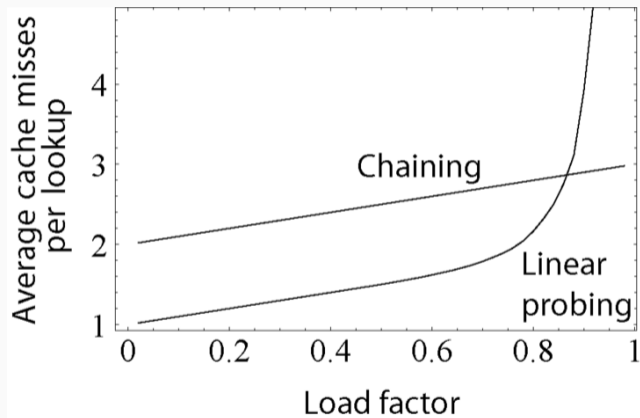
```
#define HSIZE 1000
#define STATUSFREE 0
#define STATUSUSED 1

typedef struct bucket {
    int status ;
    int key;
    int info;
} Bucket ;

typedef Bucket
    HashTable [HSIZE];
```

Ex. 6.14: Define a linear probing function and update.

Lookups: Open vs. Closed



(from Wikipedia)

Removing with Open Addressing

- `int hash(int k, int size);`
- `void initTab(HashTable h);`
- `void lookup(HashTable h, int k, int *i);`
- `void update(HashTable h, int k, int i);`
- `int find_probe (HashTable h, int k);`
- `void remove(HashTable h, int k);`

```
#define HSIZE 1000
#define STATUSFREE 0
#define STATUSUSED 1
#define STATUSDEL 2

typedef struct bucket {
    int status ;
    int key;
    int info;
} Bucket ;

typedef Bucket
    HashTable [HSIZE];
```

Ex. 6.15: How would you implement update?

How would you implement a *garbageCollect* that removes deleted cells?

What is their complexity?

**Dictionaries with trees – not for
evaluation**

We will see:

- Height- and weight-balanced tree
- Self-balancing binary search tree
 - AVL tree
 - Red-black tree

Height-balanced

- more used
- AVL: left-height = right-height ± 1
- Red-black: similar wrt *black*
- height = $\log n$

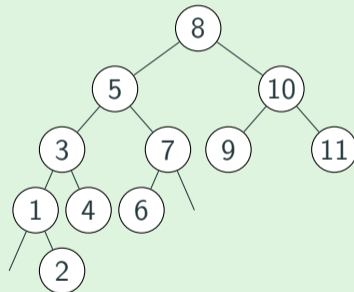
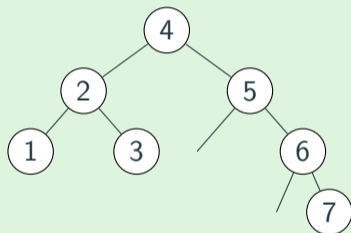
Weight-balanced

- less used
- leafs-left/right $\geq \alpha \times$ leafs, $0 < \alpha < 1$
- better for lookup intensive systems

- By Adelson-Velsky and Landis
- Oldest self-balancing binary search tree data structure to be invented ('62)
- Binary (left-right) search (sorted) tree
- Labels in the nodes
- At every node, the **height of left and right trees differ at most by 1**
- Insertions and removals preserve this

Function	Amortized	Worst Case	<i>Amortized (RB)</i>	<i>Worst case (RB)</i>
Search	$\Theta(\log n)$	$\mathcal{O}(\log n)$	$\mathcal{O}(\log n)$	$\mathcal{O}(\log n)$
Insert	$\Theta(\log n)$	$\mathcal{O}(\log n)$	$\mathcal{O}(1)$	$\mathcal{O}(\log n)$
Delete	$\Theta(\log n)$	$\mathcal{O}(\log n)$	$\mathcal{O}(1)$	$\mathcal{O}(\log n)$

Ex. 6.16: Are these balanced?



Update in an AVL tree

See animation

https://en.wikipedia.org/wiki/AVL_tree#/media/File:AVL_Tree_Example.gif

4 rotations: left, right, right-left, right-right

```
typedef struct avl {
    int bal;
    int key, info;
    struct avl *left , *right ;
} *AVL;
#define LEFT -1
#define RIGHT 1
#define BAL 0

// returns 0 if key already existed
int updateAVL (AVL *a, int k, int i);
```

Ex. 6.17: How would you implement an update without balancing?

Ex. 6.18: How would you implement AVL rotateRight(AVL a)?

Full code: updateAVL

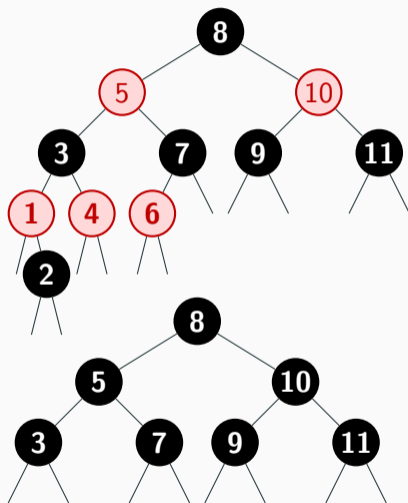
```
int updateAVL(AVL *a,
              int k, int i){
    int g, u;
    *a =
        updateAVLRec(*a,k,i,&g,&u);
    return u;
}
```

```
AVL updateAVLRec(AVL a , int k ,
                 int i, int *g , int *u){
    if (a == NULL) { // insert k->i here
        a = malloc (sizeof (struct avl ));
        a->key=k; a->info=i ; a->bal=BAL;
        a->left=a->right=NULL; *g=1; *u=0;
    } else if (a->key==k) { // update k->i
        a->info=i; *g=0; *u=1;
    } else if (a->key > k) { // update left
        a->left = updateAVLRec(a->left,k,i,g,u);
        if (*g == 1) switch (a->bal){ // balance
            case LEFT: a= fixLeft(a); *g=0; break;
            case RIGHT:a->bal=BAL; *g=0; break;
            case BAL: a->bal=LEFT; break;
        }
    } else{ // a->key < k update right
        // left <--> right
    }
    return a ;
}
```

Full code: updateAVL – fix-left

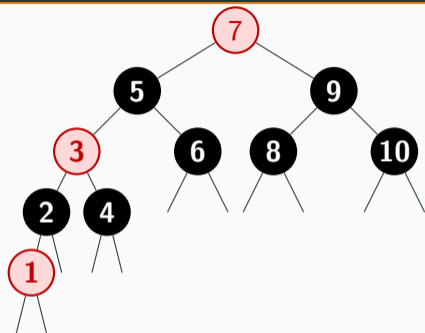
```
AVL fixLeft(AVL a) {
    AVL b, c;
    b=a->left ;
    if (b->bal==LEFT){
        a->bal = b->bal = BAL;
        a=rotateRight(a);
    } else {
        c = b->right ;
        switch (c->bal) {
            case LEFT: a->bal=RIGHT; b->bal=BAL; break;
            case RIGHT: a->bal=BAL; b->bal=LEFT; break;
            case BAL: a->bal=BAL; b->bal=BAL;
        }
        c->bal = BAL;
        a->left = rotateLeft(b);
        a = rotateRight(a);
    }
    return a;
}
```

Red-Black Trees



- 1. Nodes are black or red
- 2. Empty nodes count as black
- 3. Red nodes have only black children
- 4. All down paths from a root have equal black-height
- The root is black.
- Only 1 on the left is a RB tree

Red-Black Trees – inserting and deleting



- 6 cases for insertion (with nesting)
- 6 cases for deletion (with nesting)

Properties

- height is $\mathcal{O}(\log n)$.
- no path from the root to a leaf is more than twice as long as a path to another leaf

Function	Amortized (AVL)	Worst Case (AVL)	<i>Amortized</i>	<i>Worst case</i>
Search	$\Theta(\log n)$	$\mathcal{O}(\log n)$	$\mathcal{O}(\log n)$	$\mathcal{O}(\log n)$
Insert	$\Theta(\log n)$	$\mathcal{O}(\log n)$	$\mathcal{O}(1)$	$\mathcal{O}(\log n)$
Delete	$\Theta(\log n)$	$\mathcal{O}(\log n)$	$\mathcal{O}(1)$	$\mathcal{O}(\log n)$

Red-Black trees height is in $\mathcal{O}(\log n)$

- **1.** Nodes are black or red
- **2.** Empty nodes count as black
- **3.** Red nodes have only black children
- **4.** All down paths from a root have equal black-height

Lemma: size of a subtree – $size(x) \geq 2^{bh(x)} - 1$

- $bh(x)$ is the black-height of a node x
- **base case:** $2^{bh(\text{NULL})} - 1 = 2^0 - 1 = size(\text{NULL})$

- **inductive case:** For each child c of x :

$$bh(c) = bh(x) \text{ or } bh(c) = bh(x) - 1.$$

$$\begin{aligned} \text{Then } size(x) &\geq 2 \times (2^{bh(x)} - 1) + 1 \\ &= 2^{bh(x)+1} - 2 + 1 = 2^{bh(x)+1} - 1 \end{aligned}$$

Theorem: Height of a RB tree is $\mathcal{O}(\log n)$

- Let h be the height of a RB tree x
- For any trace $x, \dots, leaf$, more than half are black
- $\Rightarrow bh(h) \geq h/2$
- $\Rightarrow size(x) \geq 2^{h/2} - 1 \Leftrightarrow h \leq 2 \log n + 1 \in \mathcal{O}(\log n)$