COMSM1201 : Data Structures & Algorithms

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- Let's look at some toy examples to begin with.

```c
#include <stdio.h>
#include <string.h>

#define SWAP(A,B) {char temp; temp=A;A=B;B=temp;}

void strrev(char* s, int n);

int main(void)
{
    char str[] = "Hello World!";
    strrev(str, strlen(str));
    printf("%s\n", str);
    return 0;
}

/* Iterative Inplace String Reverse */
void strrev(char* s, int n)
{
    for(int i=0, j=n-1; i<j; i++, j--){
        SWAP(s[i], s[j]);
    }
}
```

Execution :

```
!dlroW olleH
```

Recursion for *strrev()*

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#include <stdio.h>
#include <string.h>

#define SWAP(A,B) {char temp; temp=A;A=B;B=temp;}

void strrev(char* s, int start, int end);

int main(void)
{
    char str[] = "Hello World!";
    strrev(str, 0, strlen(str)-1);
    printf("%s\n", str);
    return 0;
}

/* Recursive : Inplace String Reverse */
void strrev(char* s, int start, int end)
{
    if(start >= end){
        return;
    }
    SWAP(s[start], s[end]);
    strrev(s, start+1, end-1);
}
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- We need to change the function prototype.

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   strrev(s, start+1, end-1);
}
```

Execution :

```
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```

- We need to change the function prototype.
- This allows us to track both the start and the end of the string.

The Fibonacci Sequence

A well known example of a recursive function is the Fibonacci sequence. The first term is 1, the second term is 1 and each successive term is defined to be the sum of the two previous terms, i.e. :

fib(1) is 1
fib(2) is 1
fib(n) is fib(n-1)+fib(n-2)

1,1,2,3,5,8,13,21, ...

Iterative & Recursive Fibonacci

```c
#include <stdio.h>

#define MAXFIB 24

int fibonacci(int n);

int main(void)
{

    for(int i=1; i<=MAXFIB; i++){
        printf("%d = %d\n", i, fibonacci(i));
    }

    return 0;

}

int fibonacci(int n)
{
    if(n <= 2){
        return 1;
    }
    int a = 1;
    int b = 1;
    int next;
    for(int i=3; i<=n; i++){
        next = a + b;
        a = b;
        b = next;
    }
    return b;
}
```

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        a = b;
        b = next;
    }
    return b;
}
```

Execution :

```
1 = 1
2 = 1
3 = 2
4 = 3
5 = 5
6 = 8
7 = 13
8 = 21
9 = 34
10 = 55
11 = 89
12 = 144
13 = 233
14 = 377
15 = 610
16 = 987
17 = 1597
18 = 2584
19 = 4181
20 = 6765
21 = 10946
22 = 17711
23 = 28657
24 = 46368
```

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    }

    return 0;

}

int fibonacci(int n)
{
    if(n == 1) return 1;
    if(n == 2) return 1;
    return( fibonacci(n-1)+fibonacci(n-2));
}
```

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int fibonacci(int n)
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    if(n == 1) return 1;
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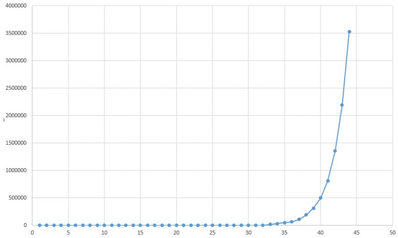
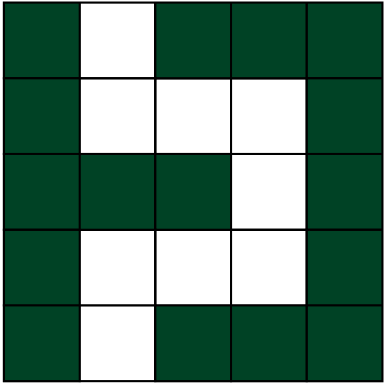
    return( fibonacci(n-1)+fibonacci(n-2));
}
```

It's interesting to see how run-time increases as the length of the sequence is raised.



Maze Escape

The correct route through a maze can be obtained via recursive, rather than iterative, methods.



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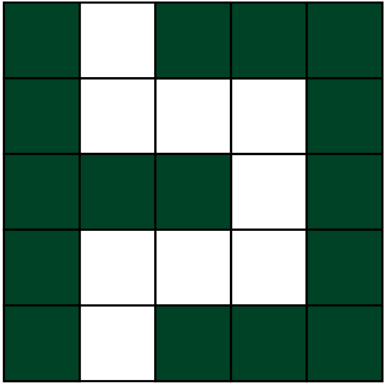

```
bool explore(int x, int y, char mz[YS][XS])
{
  if  mz[y][x] is exit return true;

  Mark mz[y][x] so we don't return here

  if we can go up :
    if(explore(x, y+1, mz)) return true

  if we can go right :
    if(explore(x+1, y, mz)) return true

  Do left & down in a similar manner

  return false; // Failed to find route
}
```

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  Execution :

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```c
// From e.g.  http://www.geeksforgeeks.org
#include <stdio.h>
#include <string.h>

#define SWAP(A,B) {char temp = *A; *A = *B; *B = temp;}

void permute(char* a, int s, int e);

int main()
{
    char str[] = "ABC";
    int n = strlen(str);
    permute(str, 0, n-1);
    return 0;
}

void permute(char* a, int s, int e)
{
    if (s == e){
      printf("%s\n", a);
      return;
    }
    for (int i = s; i <= e; i++){
       SWAP((a+s), (a+i)); // Bring one char to the front
       permute(a, s+1, e);
       SWAP((a+s), (a+i)); // Backtrack
    }
}
```

Self-test : Power

- Raising a number to a power `n = 2^5` is the same as multiple multiplications `n = 2*2*2*2*2`.

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- Or, thinking recursively, `n` = 2 * (2^4).

```c
/* Try to write power(a,b) to computer a^b
   without using any maths functions other than
   multiplication :
   Try (1) iterative then (2) recursive
   (3) Trick that for n%2==0, x^n = x^(n/2)*x^(n/2)

*/

#include <stdio.h>

int power(unsigned int a, unsigned int b);

int main(void)
{

   int x = 2;
   int y = 16;

   printf("%d^%d = %d\n", x, y, power(x,y));

}

int power(unsigned int a, unsigned int b)
{
}
```

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- Simply move through the array from beginning to end, stopping when you have found the value you require.

```c
#include <stdio.h>
#include <string.h>
#include <assert.h>

#define NOTFOUND -1
#define NUMPEOPLE 6
typedef struct person{
        char* name; int age;
} person;

int findAge(const char* name, const person* p, int n);

int main(void)
{
   person ppl[NUMPEOPLE] = { {"Ackerby", 21}, {"Bloggs", 25},
              {"Chumley", 26}, {"Dalton",  25},
              {"Eggson", 22}, {"Fulton",  41} };

   assert(findAge("Eggson",   ppl, NUMPEOPLE)==22);
   assert(findAge("Campbell", ppl, NUMPEOPLE)==NOTFOUND);
   return 0;
}

int findAge(const char* name, const person* p, int n)
{
   for(int j=0; j<n; j++){
      if(strcmp(name, p[j].name) == 0){
         return p[j].age;
      }
   }
   return NOTFOUND;
}
```

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   return 0;
}

int findAge(const char* name, const person* p, int n)
{
   for(int j=0; j<n; j++){
      int m = strcmp(name, p[j].name);
      if(m == 0) // Braces!
         return p[j].age;
      if(m < 0)
         return NOTFOUND;
   }
   return NOTFOUND;
}
```

Binary Search for *101*

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4	7	19	25	36	37	50	100	101	205	220	270	301	321
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```c
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>
#include <time.h>
#define NMBRS 1000000

int bin_it(int k, const int* a, int l, int r);

int main(void)
{
   int a[NMBRS];
   srand(time(NULL));

   // Put even numbers into array
   for(int i=0; i<NMBRS; i++){
      a[i] = 2*i;
   }

   // Do many searches for a random number
   for(int i=0; i<10*NMBRS; i++){
      int n = rand()%NMBRS;
      if((n%2) == 0){
         assert(bin_it(n, a, 0, NMBRS-1) == n/2);
      }
      else{ // No odd numbers in this list
         assert(bin_it(n, a, 0, NMBRS-1) < 0);
      }
   }
   return 0;
}
```

Iterative v. Recursion Binary Search

```
int bin_it(int k, const int* a, int l, int r)
{
    while(l <= r){
        int m = (l+r)/2;
        if(k == a[m]){
            return m;
        }
        else{
            if (k > a[m]){
                l = m + 1;
            }
            else{
                r = m - 1;
            }
        }
    }
    return -1;
}
```

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         }
         else{
            r = m - 1;
         }
      }
   }
   return -1;
}
```

```
int bin_rec(int k, const int* a, int l, int r)
{
   if(l > r) return -1;
   int m = (l+r)/2;
   if(k == a[m]){
      return m;
   }
   else{
      if (k > a[m]){
         return bin_rec(k, a, m+1, r);
      }
      else{
         return bin_rec(k, a, l, m-1);
      }
   }
}
```

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- When we look for a word in a dictionary, we don't start in the middle. We make an educated guess as to where to start based on the 1st letter of the word being searched for.

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- Now we use an interpolation involving the key, the start of the list and the end.

$$i = (k - l[0])/(l[n-1] - l[0]) * n$$

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- when searching for '15' :

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```
int interp(int k, const int* a, int l, int r)
{

    int m;
    double md;

    while(l <= r){
        md = ((double)(k-a[l])/
              (double)(a[r]-a[l])*
              (double)(r-l)
             )
             +(double)(l);
        m  = 0.5 + md;
        if((m > r) || (m < l)){
            return -1;
        }
        if(k == a[m])
            return m;
        else{
            if (k > a[m]){
                l = m + 1;
            }
            else{
                r = m- 1;
            }
        }
    }
```

Algorithmic Complexity

```c
#include <stdio.h>
#include <stdlib.h>
#include <time.h>

#define CSEC (double)(CLOCKS_PER_SEC)
#define BIGLOOP 1000000000

int main(void)
{

    clock_t c1 = clock();
    for(int i=0; i<BIGLOOP; i++){
        int j = i * 2;
    }
    clock_t c2 = clock();
    printf("%f\n", (double)(c2-c1)/CSEC);
    return 0;

}
```

- This code on an old Dell laptop took:

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  - 0.00 seconds using an aggressive optimization -O3

Algorithmic Complexity

```c
#include <stdio.h>
#include <stdlib.h>
#include <time.h>

#define CSEC (double)(CLOCKS_PER_SEC)
#define BIGLOOP 1000000000

int main(void)
{

   clock_t c1 = clock();
   for(int i=0; i<BIGLOOP; i++){
         int j = i * 2;
   }
   clock_t c2 = clock();
   printf("%f\n", (double)(c2-c1)/CSEC);
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- Binary Search : **O(log n)**

Algorithmic Complexity

```c
#include <stdio.h>
#include <stdlib.h>
#include <time.h>

#define CSEC (double)(CLOCKS_PER_SEC)
#define BIGLOOP 1000000000

int main(void)
{

    clock_t c1 = clock();
    for(int i=0; i<BIGLOOP; i++){
        int j = i * 2;
    }
    clock_t c2 = clock();
    printf("%f\n", (double)(c2-c1)/CSEC);
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}
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- This complexity indicates how, for *n* numbers, performance deteriorates when *n* changes.
- Sequential Search : **O(n)**
- Binary Search : **O(log n)**
- Interpolation Search : **O(log log n)**
- We'll discuss the dream of a **O(1)** search later in "Hashing".

Binary vs. Interpolation Timing

```
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>
#include <time.h>

int bin_it(int k, const int *a, int l, int r);
int bin_rec(int k, const int *a, int l, int r);
int interp(int k, const int *a, int l, int r);
int* parse_args(int argc, char* argv[], int* n, int* srch);

int main(int argc, char* argv[])
{

   int i, n, srch;
   int* a;
   int (*p[3])(int k, const int*a, int l, int r) =
       {bin_it, bin_rec, interp};

   a = parse_args(argc, argv, &n, &srch);

   srand(time(NULL));
   for(i=0; i<n; i++){
      a[i] = 2*i;
   }
   for(i=0; i<5000000; i++){
      assert((*p[srch])(a[rand()%n], a, 0, n-1) >= 0);
   }

   free(a);
   return 0;

}
```

Binary vs. Interpolation Timing

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#include <assert.h>
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int* parse_args(int argc, char* argv[], int* n, int* srch);

int main(int argc, char* argv[])
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    int i, n, srch;
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    int (*p[3])(int k, const int*a, int l, int r) =
        {bin_it, bin_rec, interp};

    a = parse_args(argc, argv, &n, &srch);

    srand(time(NULL));
    for(i=0; i<n; i++){
        a[i] = 2*i;
    }
    for(i=0; i<5000000; i++){
        assert((*p[srch])(a[rand()%n], a, 0, n-1) >= 0);
    }

    free(a);
    return 0;

}
```

Execution :

```
Binary Search : Iterative
n =    100000 = 0.39
n =    800000 = 0.57
n =   6400000 = 1.00
n =  51200000 = 2.46
Binary Search : Recursive
n =    100000 = 0.40
n =    800000 = 0.56
n =   6400000 = 0.97
n =  51200000 = 2.42
Interpolation
n =    100000 = 0.05
n =    800000 = 0.05
n =   6400000 = 0.10
n =  51200000 = 0.13
```

Table of Contents

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- By following pointers one after another, we can travel right along the structure.

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- Linked data representations are useful when:
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- To create linked data representations we use pointers to connect separate blocks of storage together. If a given block contains a pointer to a second block, we can follow this pointer there.
- By following pointers one after another, we can travel right along the structure.

```c
#include <stdio.h>
#include <stdlib.h>
#include "general.h"

typedef struct data{
   int i;
   struct data* next;
} Data;

Data* allocateData(int i);
void printList(Data* l);

int main(void)
{
   int i;
   Data* start, *current;
   start = current = NULL;
   printf("Enter the first number: ");
   if(scanf("%i", &i) == 1){
      start = current = allocateData(i);
   }
   else{
      on_error("Couldn't read an int");
   }

   printf("Enter more numbers: ");
   while(scanf("%i", &i) == 1){
      current->next = allocateData(i);
      current = current->next;
   }
   printList(start);
   return 0; // Should Free List
}
```

Linked Lists

```c
Data* allocateData(int i)
{
   Data* p;
   p = (Data*) ncalloc(1, sizeof(Data));
   p->i = i;
   // Not really required
   p->next = NULL;
   return p;
}

void printList(Data* l)
{
   printf("\n");
   do{
      printf("Number : %i\n", l->i);
      l = l->next;
   }while(l != NULL);
   printf("END\n");
}
```

Linked Lists

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   p->next = NULL;
   return p;
}

void printList(Data* l)
{
   printf("\n");
   do{
      printf("Number : %i\n", l->i);
      l = l->next;
   }while(l != NULL);
   printf("END\n");
}
```

Searching and Recursive printing:

```c
Data* inList(Data* n, int i)
{
   do{
      if(n->i==i){
         return n;
      }
      n = n->next;
   }while(n != NULL);
   return NULL;
}

void printList_r(Data* l)
{
   // Recursive Base-Case
   if(l == NULL) return;

   printf("Number: %i\n", l->i);
   printList_r(l->next);
}
```

Abstract Data Types

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- The **user** of the ADT doesn't need to understand how the data is being stored (e.g. array vs. linked lists etc.)
- Actually, I'll sometimes blur the boundaries of Data Structures (e.g. a linked list) with ADTs (e.g. a dictionary) themselves.

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```c
#include "../General/general.h"

typedef int colltype;

typedef struct coll coll;

#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

// Create an empty coll
coll* coll_init(void);
// Add element onto top
void coll_add(coll* c, colltype i);
// Take element out
bool coll_remove(coll* c, colltype d);
// Does this exist ?
bool coll_isin(coll* c, colltype i);
// Return size of coll
int coll_size(coll* c);
// Clears all space used
bool coll_free(coll* c);
```

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Fixed/specific.h:

```c
#pragma once

#define COLLTYPE "Fixed"

#define FIXEDSIZE 5000
struct coll {
   // Underlying array
   colltype a[FIXEDSIZE];
   int size;
};
```

Collection ADT using a Fixed-size Array

Fixed/fixed.c:

```
#include "../coll.h"
#include "specific.h"

coll* coll_init(void)
{
   coll* c = (coll*) ncalloc(1, sizeof(coll));
   c->size = 0;
   return c;
}

int coll_size(coll* c)
{
   if(c==NULL){
      return 0;
   }
   return c->size;
}

bool coll_isin(coll* c, colltype d)
{
   for(int i=0; i<coll_size(c); i++){
      if(c->a[i] == d){
         return true;
      }
   }
   return false;
}
```

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   return c;
}

int coll_size(coll* c)
{
   if(c==NULL){
      return 0;
   }
   return c->size;
}

bool coll_isin(coll* c, colltype d)
{
   for(int i=0; i<coll_size(c); i++){
      if(c->a[i] == d){
          return true;
      }
   }
   return false;
}
```

```c
void coll_add(coll* c, colltype d)
{
   if(c){
      if(c->size >= FIXEDSIZE){
         on_error("Collection overflow");
      }
      c->a[c->size] = d;
      c->size = c->size + 1;
   }
}

bool coll_remove(coll* c, colltype d)
{
   for(int i=0; i<coll_size(c); i++){
      if(c->a[i] == d){
         // Shuffle end of array left one
         for(int j=i; j<coll_size(c); j++){
            c->a[j] = c->a[j+1];
         }
         c->size = c->size - 1;
         return true;
      }
   }
   return false;
}

bool coll_free(coll* c)
{
   free(c);
   return true;
}
```

Collection ADT via an Array (Realloc)

Realloc/specific.h:

```c
#pragma once

#define COLLTYPE "Realloc"

#define INITSIZE 16
#define SCALEFACTOR 2
struct coll {
   // Underlying array
   colltype* a;
   int size;
   int capacity;
};
```

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};
```

Realloc/realloc.c:

```
#include "../coll.h"
#include "specific.h"

coll* coll_init(void)
{
   coll* c = (coll*) ncalloc(1, sizeof(coll));
   c->a = (colltype*) ncalloc(INITSIZE, sizeof(colltype));
   c->size = 0;
   c->capacity= INITSIZE;
   return c;
}

void coll_add(coll* c, colltype d)
{
   if(c){
      if(c->size >= c->capacity){
         c->a = (colltype*) nremalloc(c->a,
                sizeof(colltype)*c->capacity*SCALEFACTOR);
         c->capacity = c->capacity*SCALEFACTOR;
      }
      c->a[c->size] = d;
      c->size = c->size + 1;
   }
}
```

Collection ADT via a Linked List

Linked/specific.h:

```c
#pragma once

#define COLLTYPE "Linked"

struct dataframe {
   colltype i;
   struct dataframe* next;
};
typedef struct dataframe dataframe;

struct coll {
   // Underlying array
   dataframe* start;
   int size;
};
```

Collection ADT via a Linked List

Linked/specific.h:

```c
#pragma once

#define COLLTYPE "Linked"

struct dataframe {
   colltype i;
   struct dataframe* next;
};
typedef struct dataframe dataframe;

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   // Underlying array
   dataframe* start;
   int size;
};
```

Linked/linked.c:

```c
#include "../coll.h"
#include "specific.h"

coll* coll_init(void)
{
   coll* c = (coll*) ncalloc(1, sizeof(coll));
   return c;
}

int coll_size(coll* c)
{
   if(c==NULL){
      return 0;
   }
   return c->size;
}

bool coll_isin(coll* c, colltype d)
{
   if(c == NULL || c->start==NULL){
      return false;
   }
   dataframe* f = c->start;
   do{
      if(f->i == d){
         return true;
      }
      f = f->next;
   }while(f != NULL);
   return false;
}
```

Collection ADT via a Linked List II

```
void coll_add(coll* c, colltype d)
{
   if(c){
      dataframe* f = ncalloc(1, sizeof(dataframe));
      f->i = d;
      f->next = c->start;
      c->start = f;
      c->size = c->size + 1;
   }

}

bool coll_free(coll* c)
{
   if(c){
      dataframe* tmp;
      dataframe* p = c->start;
      while(p!=NULL){
         tmp = p->next;
         free(p);
         p = tmp;
      }
      free(c);
   }
   return true;
}
```

Collection ADT via a Linked List II

```c
void coll_add(coll* c, colltype d)
{
   if(c){
      dataframe* f = ncalloc(1, sizeof(dataframe));
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      c->start = f;
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      while(p!=NULL){
         tmp = p->next;
         free(p);
         p = tmp;
      }
      free(c);
   }
   return true;
}
```

```c
bool coll_remove(coll* c, colltype d)
{
   dataframe* f1, *f2;
   if((c==NULL) || (c->start==NULL)){
      return false;
   }

   // If Front
   if(c->start->i == d){
      f1 = c->start->next;
      free(c->start);
      c->start = f1;
      c->size = c->size - 1;
      return true;
   }

   f1 = c->start;
   f2 = c->start->next;
   do{
      if(f2->i == d){
         f1->next = f2->next;
         free(f2);
         c->size = c->size - 1;
         return true;
      }
      f1 = f2;
      f2 = f1->next;
   }while(f2 != NULL);
   return false;
}
```

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Task	Fixed Array	Realloc Array	Linked List
Insert new element	O(1) at end *if space*	O(1) at end *but realloc()*	O(1) at front
Search for an element	O(n) *brute force*	O(n) *brute force*	O(n) *brute force*
Search + delete	O(n) + O(n) *move left*	O(n) + O(n) *move left*	O(n) + O(1) *delete 'free'*

- If we had ordered our ADT (ie. the elements were sorted), then the searches could be via a binary / interpolation search, leading to O(log `n`) or O(log log `n`) search times.

ADTs Making Coding Simpler

Linked List code from the previous Chapter :

```c
#include <stdio.h>
#include <stdlib.h>
#include "general.h"

typedef struct data{
   int i;
   struct data* next;
} Data;

Data* allocateData(int i);
void printList(Data* l);

int main(void)
{
   int i;
   Data* start, *current;
   start = current = NULL;
   printf("Enter the first number: ");
   if(scanf("%i", &i) == 1){
      start = current = allocateData(i);
   }
   else{
      on_error("Couldn't read an int");
   }

   printf("Enter more numbers: ");
   while(scanf("%i", &i) == 1){
      current->next = allocateData(i);
      current = current->next;
   }
   printList(start);
   return 0; // Should Free List
}
```

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   printf("Enter the first number: ");
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   }
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   printf("Enter more numbers: ");
   while(scanf("%i", &i) == 1){
      current->next = allocateData(i);
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   }
   printList(start);
   return 0; // Should Free List
}
```

Becomes :

```c
#include "coll.h"
#include "Fixed/specific.h"

int main(void)
{
   printf("Please type some numbers :");
   coll* c = coll_init();
   int i;
   while(scanf("%i", &i) == 1){
      coll_add(c, i);
   }
   // Do print etc.
   coll_free(c);
   return 0;
}
```

Table of Contents

ADTs

At the highest level of abstraction, ADTs that we can represent using both dynamic structures (pointers) and also fixed structures (arrays) include:

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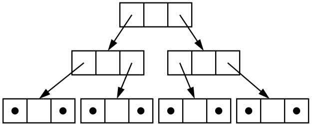
Binary Trees:



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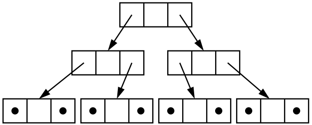
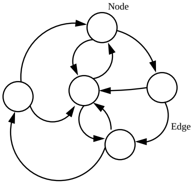
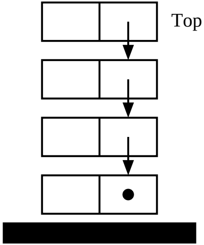


Unidirectional Graph:



Stacks

The push-down stack:



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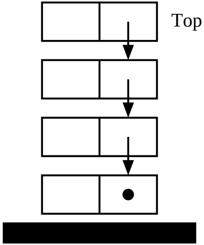

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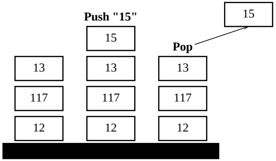

- Operations include `push` and `pop`.

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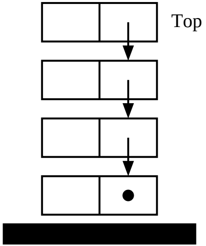

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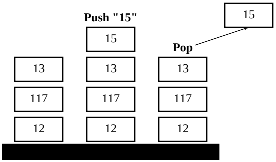

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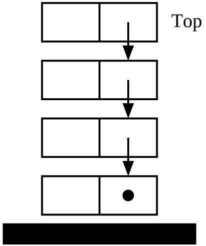

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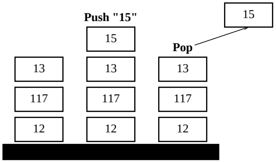

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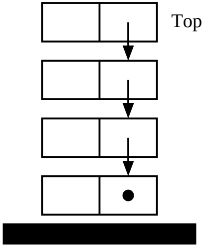

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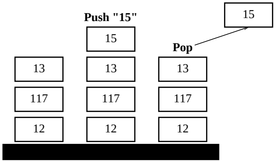

- Operations include `push` and `pop`.
- In the C run-time system, function calls are implemented using stacks.
- Most recursive algorithms can be re-written using stacks instead.
- But, once again, we are faced with the question : How best to implement such a data type ?

ADT:Stacks Arrays (Realloc) I

stack.h:

```
#pragma once

#include "../General/general.h"

typedef int stacktype;

typedef struct stack stack;

#include <stdio.h>
#include <stdlib.h>
#include <assert.h>
#include <string.h>

/* Create an empty stack */
stack* stack_init(void);
/* Add element to top */
void stack_push(stack* s, stacktype i);
/* Take element from top */
bool stack_pop(stack* s, stacktype* d);
/* Clears all space used */
bool stack_free(stack* s);

/* Optional? */

/* Copy top element into d (but don't pop it) */
bool stack_peek(stack*s, stacktype* d);
/* Make a string version - keep .dot in mind */
void stack_tostring(stack*, char* str);
```

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void stack_tostring(stack*, char* str);
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Realloc/specific.h:

```
#pragma once

#define FORMATSTR "%i"
#define ELEMSIZE 20

#define STACKTYPE "Realloc"

#define FIXEDSIZE 16
#define SCALEFACTOR 2

struct stack {
   /* Underlying array */
   stacktype* a;
   int size;
   int capacity;
};
```

ADT:Stacks Arrays (Realloc) II

Realloc/realloc.c

```c
#include "../stack.h"
#include "specific.h"

#define DOTFILE 5000

stack* stack_init(void)
{
   stack *s = (stack*) ncalloc(1, sizeof(stack));
   /* Some implementations would allow you to pass
      a hint about the initial size of the stack */
   s->a = (stacktype*) ncalloc(FIXEDSIZE, sizeof(stacktype));
   s->size = 0;
   s->capacity= FIXEDSIZE;
   return s;
}

void stack_push(stack* s, stacktype d)
{
   if(s==NULL){
       return;
   }
   if(s->size >= s->capacity){
      s->a = (stacktype*) nremalloc(s->a,
             sizeof(stacktype)*s->capacity*SCALEFACTOR);
      s->capacity = s->capacity*SCALEFACTOR;
   }
   s->a[s->size] = d;
   s->size = s->size + 1;
}
```

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stack* stack_init(void)
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   return s;
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   }
   s->a[s->size] = d;
   s->size = s->size + 1;
}
```

```c
bool stack_pop(stack* s, stacktype* d)
{
   if((s == NULL) || (s->size < 1)){
      return false;
   }
   s->size = s->size - 1;
   *d = s->a[s->size];
   return true;
}

bool stack_peek(stack* s, stacktype* d)
{
   if((s==NULL) || (s->size <= 0)){
      /* Stack is Empty */
      return false;
   }
   *d = s->a[s->size-1];
   return true;
}
```

ADT:Stacks Arrays (Realloc) III

Realloc/realloc.c

```c
void stack_tostring(stack* s, char* str)
{
   char tmp[ELEMSIZE];
   str[0] = '\0';
   if((s==NULL) || (s->size <1)){
      return;
   }
   for(int i=s->size-1; i>=0; i--){
      sprintf(tmp, FORMATSTR, s->a[i]);
      strcat(str, tmp);
      strcat(str, "|");
   }
   str[strlen(str)-1] = '\0';
}

bool stack_free(stack* s)
{
   if(s==NULL){
      return true;
   }
   free(s->a);
   free(s);
   return true;
}
```

ADT:Stacks Arrays (Realloc) III

Realloc/realloc.c

```c
void stack_tostring(stack* s, char* str)
{
   char tmp[ELEMSIZE];
   str[0] = '\0';
   if((s==NULL) || (s->size <1)){
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   }
   for(int i=s->size-1; i>=0; i--){
      sprintf(tmp, FORMATSTR, s->a[i]);
      strcat(str, tmp);
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   }
   str[strlen(str)-1] = '\0';
}

bool stack_free(stack* s)
{
   if(s==NULL){
      return true;
   }
   free(s->a);
   free(s);
   return true;
}
```

- We need a thorough testing program teststack.c

Realloc/realloc.c

```
void stack_tostring(stack* s, char* str)
{
   char tmp[ELEMSIZE];
   str[0] = '\0';
   if((s==NULL) || (s->size <1)){
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   }
   for(int i=s->size-1; i>=0; i--){
      sprintf(tmp, FORMATSTR, s->a[i]);
      strcat(str, tmp);
      strcat(str, "|");
   }
   str[strlen(str)-1] = '\0';
}

bool stack_free(stack* s)
{
   if(s==NULL){
      return true;
   }
   free(s->a);
   free(s);
   return true;
}
```

- We need a thorough testing program `teststack.c`
- See also `revstr.c` : a version of the string reverse code (for which we already seen an iterative (in-place) and a recursive solution).

ADT:Stacks Linked I

Linked/specific.h

```c
#pragma once

#define FORMATSTR "%i"
#define ELEMSIZE 20
#define STACKTYPE "Linked"

struct dataframe {
   stacktype i;
   struct dataframe* next;
};
typedef struct dataframe dataframe;

struct stack {
   /* Underlying array */
   dataframe* start;
   int size;
};
```

ADT:Stacks Linked I

Linked/specific.h

```c
#pragma once

#define FORMATSTR "%i"
#define ELEMSIZE 20
#define STACKTYPE "Linked"

struct dataframe {
   stacktype i;
   struct dataframe* next;
};
typedef struct dataframe dataframe;

struct stack {
   /* Underlying array */
   dataframe* start;
   int size;
};
```

Linked/linked.c

```c
#include "../stack.h"
#include "specific.h"

#define DOTFILE 5000

stack* stack_init(void)
{
   stack* s = (stack*) ncalloc(1, sizeof(stack));
   return s;
}

void stack_push(stack* s, stacktype d)
{
   if(s){
      dataframe* f = ncalloc(1, sizeof(dataframe));
      f->i = d;
      f->next = s->start;
      s->start = f;
      s->size = s->size + 1;
   }
}
```

ADT:Stacks Linked II

```c
bool stack_pop(stack* s, stacktype* d)
{
   if((s==NULL) || (s->start==NULL)){
      return false;
   }

   dataframe* f = s->start->next;
   *d = s->start->i;
   free(s->start);
   s->start = f;
   s->size = s->size - 1;
   return true;
}

bool stack_peek(stack* s, stacktype* d)
{
   if((s==NULL) || (s->start==NULL)){
      return false;
   }
   *d = s->start->i;
   return true;
}
```

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```c
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{
    if((s==NULL) || (s->start==NULL)){
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    dataframe* f = s->start->next;
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    }
    *d = s->start->i;
    return true;
}
```

```c
void stack_tostring(stack* s, char* str)
{
    char tmp[ELEMSIZE];
    str[0] = '\0';
    if((s==NULL) || (s->size <1)){
        return;
    }
    dataframe* p = s->start;
    while(p){
        sprintf(tmp, FORMATSTR, p->i);
        strcat(str, tmp);
        strcat(str, "|");
        p = p->next;
    }
    str[strlen(str)-1] = '\0';
}

bool stack_free(stack* s)
{
    if(s){
        dataframe* p = s->start;
        while(p!=NULL){
            dataframe* tmp = p->next;
            free(p);
            p = tmp;
        }
        free(s);
    }
    return true;
}
```

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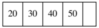
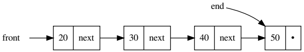
FIFO (First in, First out):





- Intuitively more "useful" than a stack.

ADTs : Queues

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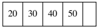

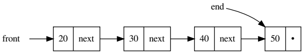

- Intuitively more “useful” than a stack.
- Think of implementing any kind of service (printer, web etc.)

ADTs : Queues

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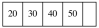
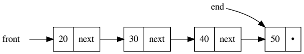
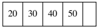
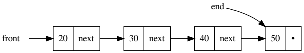




- Intuitively more "useful" than a stack.
- Think of implementing any kind of service (printer, web etc.)
- Operations include `enqueue`, `dequeue` and `size`.

FIFO (First in, First out):





- Intuitively more “useful” than a stack.
- Think of implementing any kind of service (printer, web etc.)
- Operations include `enqueue`, `dequeue` and `size`.

ADTs : Queues

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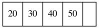

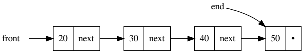

- Intuitively more “useful” than a stack.
- Think of implementing any kind of service (printer, web etc.)
- Operations include enqueue, dequeue and size.

queue.h

```c
#pragma once

#include "../General/general.h"

typedef int queuetype;

typedef struct queue queue;

#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <assert.h>

/* Create an empty queue */
queue* queue_init(void);
/* Add element on end */
void queue_enqueue(queue* q, queuetype v);
/* Take element off front */
bool queue_dequeue(queue* q, queuetype* d);
/* Return size of queue */
int queue_size(queue* q);
/* Clears all space used */
bool queue_free(queue* q);

/* Helps with visualisation & testing */
void queue_tostring(queue* q, char* str);
```

ADTs : Queues (Fixed) I

specific.h

```c
#pragma once

#define FORMATSTR "%d"
#define ELEMSIZE 20

#define QUEUETYPE "Fixed"

#define BOUNDED 5000

struct queue {
   /* Underlying array */
   queuetype a[BOUNDED];
   int front;
   int end;
};

#define DOTFILE 5000
```

ADTs : Queues (Fixed) I

specific.h

```
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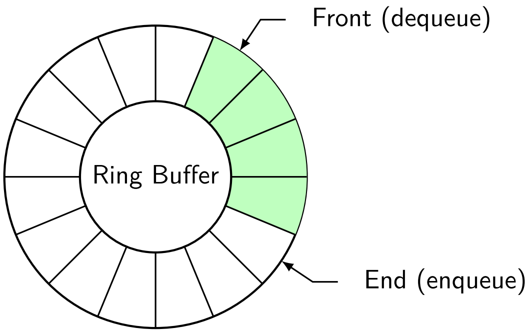

ADTs : Queues (Fixed) II

fixed.c

```c
#include "../queue.h"
#include "specific.h"

void _inc(int* p);

queue* queue_init(void)
{
   queue* q = (queue*) ncalloc(1, sizeof(queue));
   return q;
}


void queue_enqueue(queue* q, queuetype d)
{
   if(q){
      q->a[q->end] = d;
      _inc(&q->end);
      if(q->end == q->front){
         on_error("Queue too large");
      }
   }
}
```

ADTs : Queues (Fixed) II

fixed.c

```c
#include "../queue.h"
#include "specific.h"

void _inc(int* p);

queue* queue_init(void)
{
   queue* q = (queue*) ncalloc(1, sizeof(queue));
   return q;
}


void queue_enqueue(queue* q, queuetype d)
{
   if(q){
      q->a[q->end] = d;
      _inc(&q->end);
      if(q->end == q->front){
         on_error("Queue too large");
      }
   }
}
```

```c
bool queue_dequeue(queue* q, queuetype* d)
{
   if((q==NULL) || (q->front==q->end)){
      return false;
   }
   *d = q->a[q->front];
   _inc(&q->front);
   return true;
}

void queue_tostring(queue* q, char* str)
{
   char tmp[ELEMSIZE];
   str[0] = '\0';
   if((q==NULL) || (queue_size(q)==0)){
      return;
   }
   for(int i=q->front; i != q->end;){
      sprintf(tmp, FORMATSTR, q->a[i]);
      strcat(str, tmp);
      strcat(str, "|");
      _inc(&i);
   }
   str[strlen(str)-1] = '\0';
}
```

ADTs : Queues (Fixed) III

```
int queue_size(queue* q)
{
   if(q==NULL){
      return 0;
   }
   if(q->end >= q->front){
      return q->end-q->front;
   }
   return q->end + BOUNDED - q->front;
}

bool queue_free(queue* q)
{
   free(q);
   return true;
}

void _inc(int* p)
{
   *p = (*p + 1) % BOUNDED;
}
```

ADTs : Queues (Fixed) III

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int queue_size(queue* q)
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- We need a thorough testing program

ADTs : Queues (Fixed) III

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- We need a thorough testing program
- We'll see queues again for traversing trees

ADTs : Queues (Fixed) III

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int queue_size(queue* q)
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   if(q==NULL){
      return 0;
   }
   if(q->end >= q->front){
      return q->end-q->front;
   }
   return q->end + BOUNDED - q->front;
}

bool queue_free(queue* q)
{
   free(q);
   return true;
}

void _inc(int* p)
{
   *p = (*p + 1) % BOUNDED;
}
```

- We need a thorough testing program
- We'll see queues again for traversing trees
- Simulating a (slow) printer

ADTs : Queues (Linked) I

specific.h

```c
#pragma once

#define FORMATSTR "%d"
#define ELEMSIZE 20

#define QUEUETYPE "Linked"

struct dataframe {
   queuetype i;
   struct dataframe* next;
};
typedef struct dataframe dataframe;

struct queue {
   /* Underlying array */
   dataframe* front;
   dataframe* end;
   int size;
};
```

ADTs : Queues (Linked) I

specific.h

```c
#pragma once

#define FORMATSTR "%d"
#define ELEMSIZE 20

#define QUEUETYPE "Linked"

struct dataframe {
   queuetype i;
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};
typedef struct dataframe dataframe;

struct queue {
   /* Underlying array */
   dataframe* front;
   dataframe* end;
   int size;
};
```

linked.c

```c
#include "../queue.h"
#include "specific.h"

queue* queue_init(void)
{
   queue* q = (queue*) ncalloc(1, sizeof(queue));
   return q;
}

void queue_enqueue(queue* q, queuetype d)
{
   dataframe* f;
   if(q==NULL){
      return;
   }

   /* Copy the data */
   f = ncalloc(1, sizeof(dataframe));
   f->i = d;

   /* 1st one */
   if(q->front == NULL){
      q->front = f;
      q->end = f;
      q->size = q->size + 1;
      return;
   }
   /* Not 1st */
   q->end->next = f;
   q->end = f;
   q->size = q->size + 1;
}
```

ADTs : Queues (Linked) II

```
bool queue_dequeue(queue* q, queuetype* d)
{
   dataframe* f;
   if((q==NULL) || (q->front==NULL) || (q->end==NULL)){
      return false;
   }
   f = q->front->next;
   *d = q->front->i;
   free(q->front);
   q->front = f;
   q->size = q->size - 1;
   return true;
}

bool queue_free(queue* q)
{
   if(q){
      dataframe* tmp;
      dataframe* p = q->front;
      while(p!=NULL){
         tmp = p->next;
         free(p);
         p = tmp;
      }
      free(q);
   }
   return true;
}
```

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bool queue_dequeue(queue* q, queuetype* d)
{
    dataframe* f;
    if((q==NULL) || (q->front==NULL) || (q->end==NULL)){
        return false;
    }
    f = q->front->next;
    *d = q->front->i;
    free(q->front);
    q->front = f;
    q->size = q->size - 1;
    return true;
}

bool queue_free(queue* q)
{
    if(q){
        dataframe* tmp;
        dataframe* p = q->front;
        while(p!=NULL){
            tmp = p->next;
            free(p);
            p = tmp;
        }
        free(q);
    }
    return true;
}
```

```c
void queue_tostring(queue* q, char* str)
{
    dataframe *p;
    char tmp[ELEMSIZE];
    str[0] = '\0';
    if((q==NULL) || (q->front == NULL)){
        return;
    }
    p = q->front;
    while(p){
        sprintf(tmp, FORMATSTR, p->i);
        strcat(str, tmp);
        strcat(str, "|");
        p = p->next;
    }
    str[strlen(str)-1] = '\0';
}

int queue_size(queue* q)
{
    if((q==NULL) || (q->front==NULL)){

        return 0;
    }
    return q->size;
}
```

Detour : Graphviz

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  digraph {
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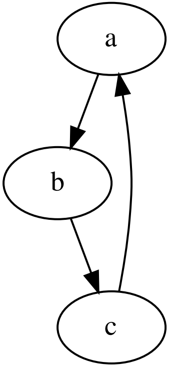

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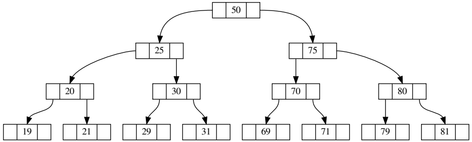

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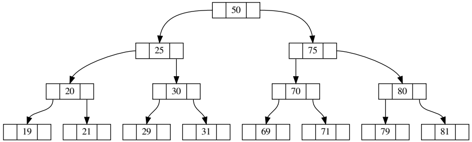

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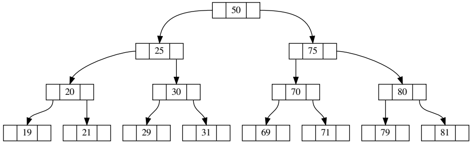

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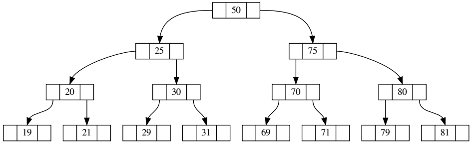

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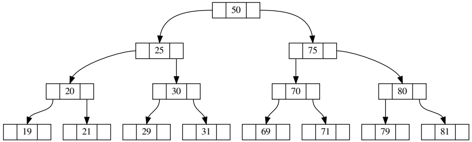

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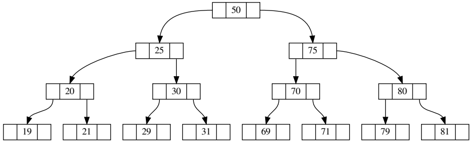

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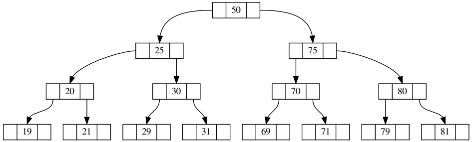

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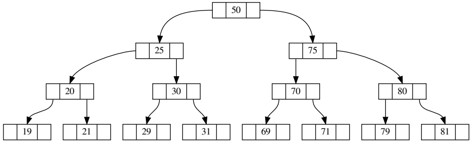

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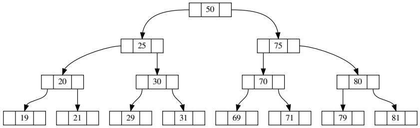
- Can refer to left and right children
- In a tree, there is only one path from the root to any child
- A node with no children is a leaf
- Most trees need to be created dynamically
- Empty subtrees are set to NULL

Binary Search Trees

In a binary search tree the left-hand tree of a parent contains all keys less than the parent node, and the right-hand side all the keys greater than the parent node.



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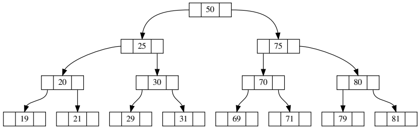

bst.h

```c
#include "../General/general.h"
#include "../Queue/queue.h"

#include <stdio.h>
#include <stdlib.h>
#include <assert.h>

bst* bst_init(void);

/* Insert 1 item into the tree */
bool bst_insert(bst* b, treetype d);

/* Return number of nodes in tree */
int bst_size(bst* b);

/* Whether the data d is stored in the tree */
bool bst_isin(bst* b, treetype d);

/* Bulk insert n items from an array a into an initialised tree */
bool bst_insertarray(bst* b, treetype* a, int n);

/* Clear all memory associated with tree, & set pointer to NULL */
bool bst_free(bst* b);

/* Optional ? */

char* bst_preorder(bst* b);
void bst_printlevel(bst* b);
/* Create string with tree as ((head)(left)(right)) */
char* bst_printlisp(bst* b);
/* Use Graphviz via a .dot file */
void bst_todot(bst* b, char* dotname);
```

Binary Search Trees : Linked I

specific.h

```
#include <string.h>

typedef int treetype;
#define FORMATSTR "%i"
#define ELEMSIZE 20
#define BSTTYPE "Linked"

struct dataframe {
   treetype d;
   struct dataframe* left;
   struct dataframe* right;
};
typedef struct dataframe dataframe;

struct bst {
   dataframe* top;
   /* Data element size, in bytes */
};
typedef struct bst bst;
```

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struct bst {
   dataframe* top;
   /* Data element size, in bytes */
};
typedef struct bst bst;
```

```c
/* Based on geekforgeeks.org */
dataframe* _insert(dataframe* t, treetype d)
{
    dataframe* f;
    /* If the tree is empty, return a new frame */
    if (t == NULL){
       f = ncalloc(sizeof(dataframe), 1);
       f->d = d;
       return f;
    }
    /* Otherwise, recurs down the tree */
    if (d < t->d){
        t->left = _insert(t->left, d);
    }
    else if(d > t->d){
       t->right = _insert(t->right, d);
    }
    /* return the (unchanged) dataframe pointer */
    return t;
}
```

Binary Search Trees : Linked II

```
bool _isin(dataframe* t, treetype d)
{
   if(t==NULL){
      return false;
   }
   if(t->d == d){
      return true;
   }
   if(d < t->d){
      return _isin(t->left,  d);
   }
   else{
      return _isin(t->right, d);
   }
   return false;
}
```

Binary Search Trees : Linked II

```c
bool _isin(dataframe* t, treetype d)
{
   if(t==NULL){
      return false;
   }
   if(t->d == d){
      return true;
   }
   if(d < t->d){
      return _isin(t->left, d);
   }
   else{
      return _isin(t->right, d);
   }
   return false;
}
```

```c
char* _printlisp(dataframe* t)
{
   char tmp[ELEMSIZE];
   char *s1, *s2, *p;

   if(t==NULL){
      /* \0 string */
      p = ncalloc(1,1);
      return p;
   }
   sprintf(tmp, FORMATSTR, t->d);
   s1 = _printlisp(t->left);
   s2 = _printlisp(t->right);
   p = ncalloc(strlen(s1)+strlen(s2)+strlen(tmp)+
        strlen("()() "), 1);
   sprintf(p, "%s(%s)(%s)", tmp, s1, s2);
   free(s1);
   free(s2);
   return p;
}
```

Binary Trees using Arrays ?

- Don't rush to assume a linked data structure must be used to implement trees.

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- You could use 1 cell of an array for the first node, the next two cells for its children, the next 4 cells for their children and so on.

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Counting from cell 1, for a tree with n nodes:

To find	Use	Iff
The root	$A[1]$	A is nonempty
The left child of $A[i]$	$A[2i]$	$2i \leq n$
The parent of $A[i]$	$A[i/2]$	$i > 1$
Is $A[i]$ a leaf ?	True	$2i > n$

Binary Search Trees : Realloc

specific.h

```
#include <stdbool.h>

typedef int treetype;
#define FORMATSTR "%i"
#define ELEMSIZE 20
#define BSTTYPE "Realloc"

// Probably (2^n) -1
#define INITSIZE 31
#define SCALEFACTOR 2

struct dataframe {
   treetype d;
   bool isvalid;
};
typedef struct dataframe dataframe;

struct bst {
   dataframe* a;
   int capacity;
};
typedef struct bst bst;
```

Binary Search Trees : Realloc

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typedef int treetype;
#define FORMATSTR "%i"
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// Probably (2^n) -1
#define INITSIZE 31
#define SCALEFACTOR 2

struct dataframe {
   treetype d;
   bool isvalid;
};
typedef struct dataframe dataframe;

struct bst {
   dataframe* a;
   int capacity;
};
typedef struct bst bst;
```

Using a queue for Level-Order traversal:

```c
void bst_printlevel(bst* b)
{
   treetype n;
   if((b==NULL) || (! _isvalid(b, 0))){
      return;
   }
   /* Make a queue of cell indices */
   queue* q = queue_init();
   queue_enqueue(q, 0);
   while(queue_dequeue(q, &n) && _isvalid(b, (int)n)){
      printf(FORMATSTR, b->a[n].d);
      putchar(' ');
      queue_enqueue(q, _leftchild((int)n));
      queue_enqueue(q, _rightchild((int)n));
   }
```

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- Large body of literature about creating & re-balancing trees - Red-Black trees, Tries, 2-3 trees, AVL trees etc.

Binary Trees : Huffman Compression I

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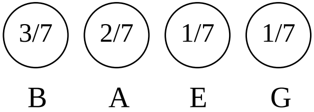

- Keep a list of characters, ordered by their frequency

Binary Trees : Huffman Compression II

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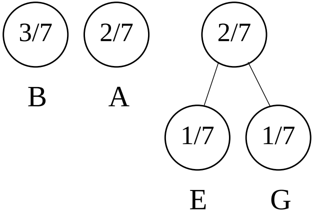

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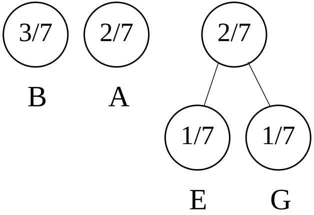

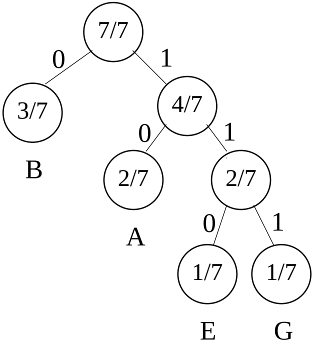

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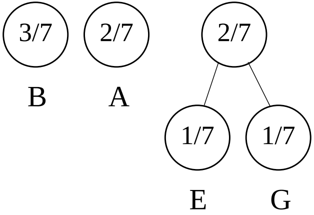

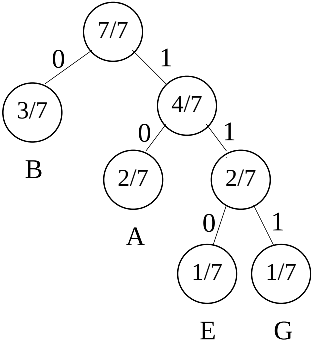

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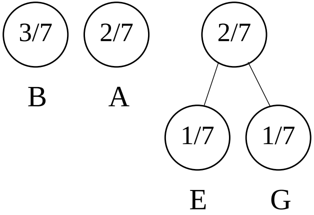

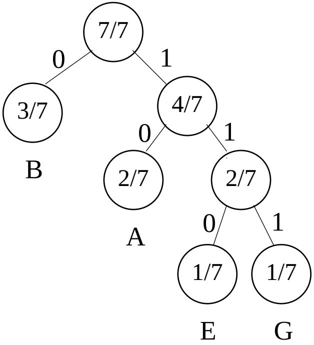

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Table of Contents

ADTs : Hashing

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- As an example lets use an array of size 11 to store some airport codes, e.g. PEK, BRS, FRA.

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- Inserting "PHL", "ORY" and "GCM":

	0
	1
	2
	3
PHL	4
	5
GCM	6
	7
ORY	8
	9
	10

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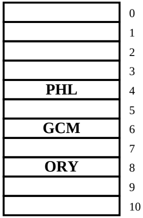
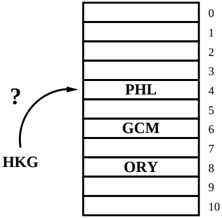


- However, inserting "HKG" causes a collision.



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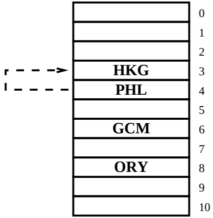

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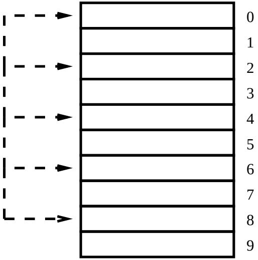
- Although "PHL" and "HKG" share the same primary hash value of $h(K) = 4$, they have different probe decrements:
  $p(''PHL'') = 4$
  $p(''HKG'') = 3$

Hashing : Primes and Chaining

- If the size of our array, M, was even and the probe decrement was chosen to be 2, then only half of the locations could be probed.



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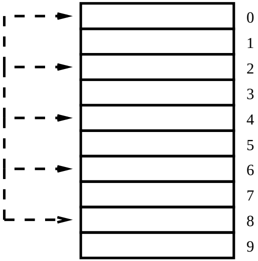

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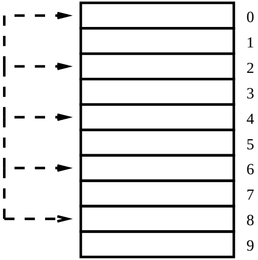

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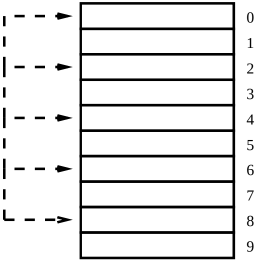

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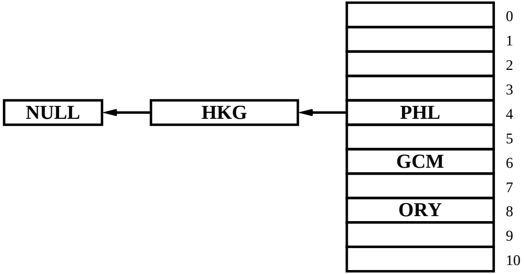
Open-addressing is not the only method of collision reduction. Another common one is separate chaining.



A Practical Hash Function

```c
#include <stdio.h>

int hash(unsigned int sz, char *s);

int main(void)
{

   char str[] = "Hello World!";
   // Hash modulus 7919
   printf("%d\n", hash(7919, str));
   return 0;

}

/*
Modified Bernstein hashing
5381 & 33 are magic numbers required by the algorithm
*/
int hash(unsigned int sz, char *s)
{
   unsigned long hash = 5381;
   int c;
   while((c = (*s++))){
      hash = 33 * hash ^ c;
   }
   return (int)(hash%sz);
}
```

Execution :

```
5479
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5479
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Has similarities to the implementation of `rand()` :

```c
int rand_r(unsigned int* seed);

int main(void)
{
   unsigned int seed = 0;
   printf("%d\n", rand_r(&seed));
   return 0;
}

/* This algorithm is mentioned in the ISO C standard,
   here extended for 32 bits. */
int rand_r(unsigned int* seed)
{
  unsigned int next = *seed;
  int result;
  next *= 1103515245;
  next += 12345;
  result = (unsigned int) (next / 65536) % 2048;
  next *= 1103515245;
  next += 12345;
  result <<= 10;
  result ^= (unsigned int) (next / 65536) % 1024;
  next *= 1103515245;
  next += 12345;
  result <<= 10;
  result ^= (unsigned int) (next / 65536) % 1024;
  *seed = next;
  return result;
```

Execution :

```
1012484
```

Cuckoo Hashing

- We have two tables, each with their **own** hash function.

```
Empty: copied farandoles into table 0(4)
Empty: copied bronzine into table 0(12)
Empty: copied auscultatory into table 0(5)
Empty: copied bifer into table 0(13)
Empty: copied steepgrass into table 0(6)
Empty: copied prevised into table 0(7)
Empty: copied oomph into table 0(8)
empodium, so cuckooed out auscultatory from table 0(5)
Empty: copied auscultatory into table 1(10)
interquarreled, so cuckooed out bronzine from table 0(12)
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ranseur, so cuckooed out empodium from table 0(5)
Empty: copied empodium into table 1(4)
Empty: copied megalodon into table 0(11)
geosynchronous, so cuckooed out megalodon from table 0(11)
Empty: copied megalodon into table 1(14)
Empty: copied osmeteria into table 0(14)
Table getting full -> rehashed old sz =16
```

Cuckoo Hashing

- We have two tables, each with their **own** hash function.
- We only need to check two cells when searching.

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Table getting full -> rehashed old sz =16
```

Cuckoo Hashing

- We have two tables, each with their **own** hash function.
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Empty: copied auscultatory into table 0(5)
Empty: copied bifer into table 0(13)
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Empty: copied prevised into table 0(7)
Empty: copied oomph into table 0(8)
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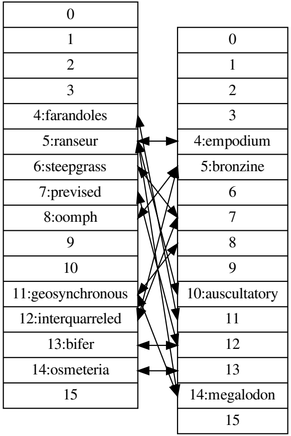

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void bubble_sort(int b[], int s);

int main(void)
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    int a[] = {3, 4, 1, 2, 9, 0};
    bubble_sort(a, NUMS);
    for(int i=0; i<NUMS; i++){
        printf("%i ", a[i]);
    }
    printf("\n");
    return 0;
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void bubble_sort(int b[], int s)
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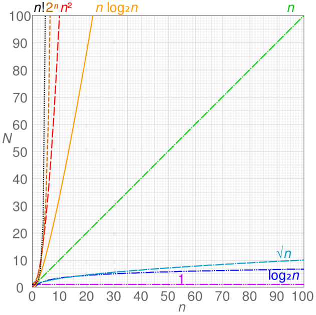

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#include <stdio.h>
#include <stdlib.h>
#include <string.h>

void mergesort(int *src, int *spare, int l, int r);
void merge(int *src, int *spare, int l, int m, int r);

#define NUM 5000

int main(void)
{
    int a[NUM];
    int spare[NUM];

    for(int i=0; i<NUM; i++){
        a[i] = rand()%100;
    }

    mergesort(a, spare, 0, NUM-1);

    for(int i=0; i<NUM; i++){
        printf("%4d => %d\n", i, a[i]);
    }

    return 0;
}
```

Merge Sort II

```
void mergesort(int *src, int *spare, int l, int r)
{
    int m = (l+r)/2;
    if(l != r){
        mergesort(src, spare, l, m);
        mergesort(src, spare, m+1, r);
        merge(src, spare, l, m, r);
    }
}

void merge(int *src, int *spare, int l, int m, int r)
{
    int s1 = l;
    int s2 = m+1;
    int d = l;

    do{
        if(src[s1] < src[s2]){
            spare[d++] = src[s1++];
        }
        else{
            spare[d++] = src[s2++];
        }
    }while((s1 <= m) && (s2 <= r));

    if(s1 > m){
        memcpy(&spare[d], &src[s2], sizeof(spare[0])*(r-s2+1));
    }
    else{
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- Once again, the sort is then applied recursively.

Algorithms : Quicksort

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#include <stdlib.h>
#include <math.h>

int partition(int *a, int l, int r);
void quicksort(int *a, int l, int r);

#define NUM 100000

int main(void)
{
    int a[NUM];

    for(int i=0; i<NUM; i++){
        a[i] = rand()%100;
    }
    quicksort(a, 0, NUM-1);

    return 0;
}

void quicksort(int *a, int l, int r)
{
    int pivpoint = partition(a, l, r);
    if(l < pivpoint){
        quicksort(a, l, pivpoint-1);
    }
    if(r > pivpoint){
        quicksort(a, pivpoint+1, r);
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    return 0;
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    int pivpoint = partition(a, l, r);
    if(l < pivpoint){
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    }
    if(r > pivpoint){
        quicksort(a, pivpoint+1, r);
    }
}
```

```c
int partition(int *a, int l, int r)
{
    int piv = a[l];
    while(l<r){
        /* Right -> Left Scan */
        while(piv < a[r] && l<r) r--;
        if(r!=l){
            a[l] = a[r];
            l++;
        }
        /* Left -> Right Scan */
        while(piv > a[l] && l<r) l++;
        if(r!=l){
            a[r] = a[l];
            r--;
        }
    }
    a[r] = piv;
    return r;
}
```

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```c
#include <stdio.h>
#include <stdlib.h>

int intcompare(const void *a, const void *b);

int main(void)
{
   int a[10];

   for(int i=0; i<10; i++){
      a[i] = 9 - i;
   }

   qsort(a, 10, sizeof(int), intcompare);

   for (int i=0; i<10; i++){
      printf(" %d",a[i]);
   }
   printf("\n");
   return 0;

}

int intcompare(const void *a, const void *b)
{
    const int *ia = (const int *)a;
    const int *ib = (const int *)b;
    return *ia  - *ib;
}
```

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459 254 472 534 649 239 432 654 477

0
1
2 472 432
3
4 254 534 654
5
6
7 477
8
9 459 649 239

Read out the new list:
472 432 254 534 654 477 459 649 239

Radix Sort II

472 432 254 534 654 477 459 649 239

0
1
2
3 432 534 239
4 649
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6
7 472 477
8
9

432 534 239 649 254 654 459 472 477

Radix Sort II

472 432 254 534 654 477 459 649 239

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Radix Sort Discussion and gprof

- This has a theoretical complexity of $O(n)$.
- It is difficult to write an all-purpose radix sort - you need a different one for doubles, integers, strings etc.
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- Now: `gprof ./executable gmon.out` shows the function-call profile of your code.

Table of Contents

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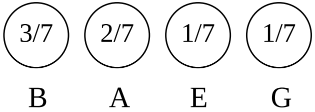

- Keep a list of characters, ordered by their frequency

Huffman Compression II

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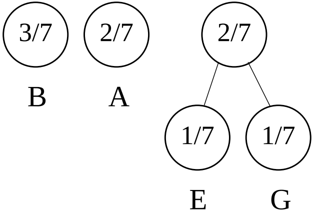

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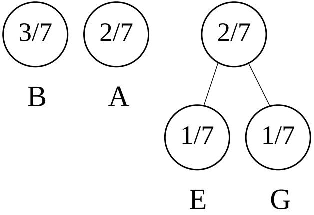

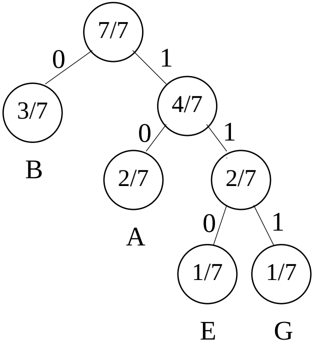

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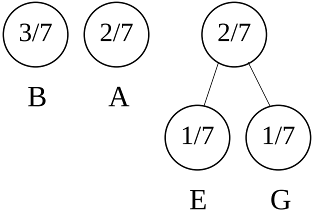

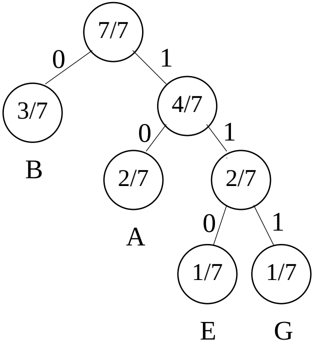

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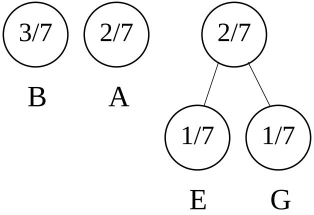

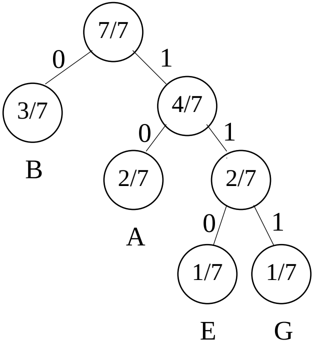

- A = 10, B = 0, E = 110, G = 111
- String stored using 13 bits.

Algorithm : Rabin-Karp String Searching

- The task of searching for a string amongst a large amount of text is commonly required in word-processors, but more interestingly in massive Biological Databases e.g. searching for amino acids in protein sequences.

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Master String : AAAAAAAAAAAAAH
Substring     : AAAAAAH
Substring     :  AAAAAAH
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- Recall that to compute a hash function on a word we did something like:

$$h("NEILL") =$$

$$(13 \times 26^4 + 4 \times 26^3 + 8 \times 26^2 + 11 \times 26 + 11)\%P$$

where P is a big prime number.

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  where P is a big prime number.
- This can be expanded by Horner's method to:

$$((((((13 \times 26) + 4) \times 26) + 8) \times 26) + 11) \times 26 + 11)\%P$$

Rabin-Karp II

- For a large search string, overflow can occur. We therefore move the *mod* operation inside the brackets:

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```c
#include <string.h>
#include <assert.h>

#define Q 33554393
#define D 26
#define index(C) (C-'A')

int rk(char *p, char *a);

int main(void)
{
   assert(rk("STING",
          "A STRING EXAMPLE CONSISTING OF ...")==22);
   return 0;
}

int rk(char *p, char *a)
{
   int i, dM = 1, h1=0, h2=0;
   int m = strlen(p);
   int n = strlen(a);
   for(i=1; i<m; i++) dM = (D*dM)%Q;
   for(i=0; i<m; i++){
      h1 = (h1*D+index(p[i]))%Q;
      h2 = (h2*D+index(a[i]))%Q;
   }
   // h1 = search string hash, h2 = master string hash
   for(i=0; h1!=h2; i++){
      h2 = (h2+D*Q-index(a[i])*dM) % Q;
      h2 = (h2*D+index(a[i+m])) % Q;
      if(i>n-m) return n;
   }
   return i;
}
```

Algorithm : Boyer-Moore String Searching

The Boyer-Moore algorithm uses (in part) an array flagging which characters form part of the search string and an array telling us how far to slide right if that character appears in the master and causes a mismatch.

Execution :

```
A STRING SEARCHING EXAMPLE CONSISTING OF ...
     |     |
STING      |
     STING
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- Since R doesn't appear in the search string, we can take 5 steps to the right.
- The next comparison is between the G and the S. We can slide the search string right until it matches the S in the master.

Boyer-Moore II

Execution :

```
A STRING SEARCHING EXAMPLE CONSISTING OF ...
             |    |    |    |    |
         STING    |    |    |    |
              STING    |    |    |
                   STING    |    |
                        STING    |
                             STING
```

- Now the C doesn't appear in the master and once again we can slide a full 5 places to the right.

Boyer-Moore II

Execution :

```
A STRING SEARCHING EXAMPLE CONSISTING OF ...
         |    |    |    |    |
     STING    |    |    |    |
          STING    |    |    |
               STING    |    |
                    STING    |
                         STING
```

- Now the C doesn't appear in the master and once again we can slide a full 5 places to the right.
- After 3 more full slides right we arrive at the T in CONSISTING.

Boyer-Moore II

Execution :

```
A STRING SEARCHING EXAMPLE CONSISTING OF ...
          |     |     |     |     |
       STING    |     |     |     |
             STING    |     |     |
                   STING    |     |
                         STING    |
                               STING
```

- Now the C doesn't appear in the master and once again we can slide a full 5 places to the right.
- After 3 more full slides right we arrive at the T in CONSISTING.
- We align the T's, and have found our match using 7 compares (plus 5 to verify the match).

Table of Contents

ADTs : Graphs

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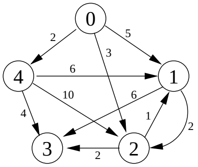

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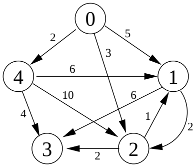

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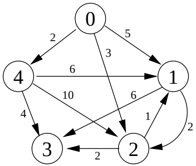

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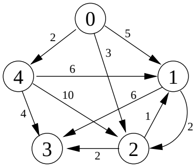

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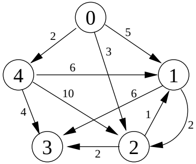

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- Every edge has a non-negative weight attached which may correspond to time, distance, cost etc.

graph.h (partial)

```
#include <limits.h>
#define INF (INT_MAX)

/* Initialise an empty graph */
graph* graph_init(void);

/* Add new vertex */
int graph_addVert(graph* g, char* label);

/* Add new edge between two Vertices */
bool graph_addEdge(graph* g,  int from,
                   int to, edge weight);

/* Returns NO_VERT if not already a vert
   else 0 ... (size-1)                    */
int graph_getVertNum(graph* g, char* label);

/* Returns label of vertex v */
char* graph_getLabel(graph* g, int v);

/* Returns edge weight - if none = INF */
edge graph_getEdgeWeight(graph* g, int from, int to);

/* Number of verts */
int graph_numVerts(graph* b);

/* Output edge weights e.g. "0->1 200 2->1 100" */
void graph_tostring(graph* g, char* str);

/* Clear all memory associated with graph */
bool graph_free(graph* g);
```

Graph ADT : 2D Realloc I

The graph type could be implemented in a large number of different ways.

- As two sets, one for vertices, one for edges. We haven't looked at an implentation for sets, but one could use lists.

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	0	**1**	**2**	**3**	**4**
0	0	5	3	∞	2
1	∞	0	2	6	∞
2	∞	1	0	2	∞
3	∞	∞	∞	0	∞
4	∞	6	10	4	0

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2	∞	1	0	2	∞
3	∞	∞	∞	0	∞
4	∞	6	10	4	0

specific.h

```c
#define GRAPHTYPE "Realloc"

#define INITSIZE 8
#define SCALEFACTOR 2

#define TMPSTR 1000

#define NO_VERT -1

typedef unsigned int edge;

struct graph {
   edge** adjMat;
   char** labels;
   /* Actual number of verts */
   int size;
   /* Max verts before realloc() */
   int capacity;
};
typedef struct graph graph;
```

2D Realloc II

```c
graph* graph_init(void)
{
   graph* g = (graph*) ncalloc(sizeof(graph), 1);
   int h = INITSIZE;
   int w = h;
   g->capacity = h;
   g->adjMat = (edge**) n2dcalloc(h, w, sizeof(edge));
   g->labels = (char**) n2dcalloc(h, MAXLABEL+1, sizeof(char));
   for(int j=0; j<h; j++){
      for(int i=0; i<w; i++){
         /* It's not clear if weight[j][j] should be 0 or INF */
         g->adjMat[j][i] = INF;
      }
   }
   return g;
}

edge graph_getEdgeWeight(graph* g, int from, int to)
{
   if((g==NULL) || (from >= g->size) || (to >= g->size)){
      return INF;
   }
   return g->adjMat[from][to];
}


int graph_numVerts(graph* g)
{
   if(g==NULL){
      return 0;
   }
   return g->size;
}
```

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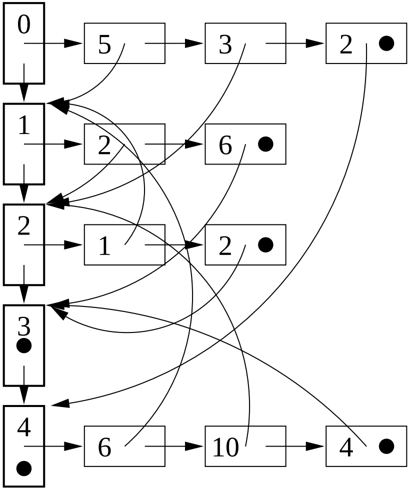
   return g->size;
}
```

```c
int graph_addVert(graph* g, char* label)
{
   if(g==NULL){
      return NO_VERT;
   }
   if(graph_getVertNum(g, label) != NO_VERT){
      return NO_VERT;
   }
   /* Resize */
   if(g->size >= g->capacity){
      g->adjMat = (edge**) n2drecalloc((void**)g->adjMat,
                  g->capacity, g->capacity*SCALEFACTOR,
                  g->capacity, g->capacity*SCALEFACTOR,
                  sizeof(edge));
      g->labels = (char**) n2drecalloc((void**)g->labels,
                  g->capacity, g->capacity*SCALEFACTOR,
                  MAXLABEL+1, MAXLABEL+1,  1);
      for(int j=0; j<g->capacity*SCALEFACTOR; j++){
         for(int i=0; i<g->capacity*SCALEFACTOR; i++){
            if((i>=g->capacity)||(j>=g->capacity)){
               g->adjMat[j][i] = INF;
            }
         }
      }
      g->capacity = g->capacity*SCALEFACTOR;
   }
   strcpy(g->labels[g->size], label);
   g->size = g->size + 1;
   return g->size-1;
}
```

Graph ADT - Linked



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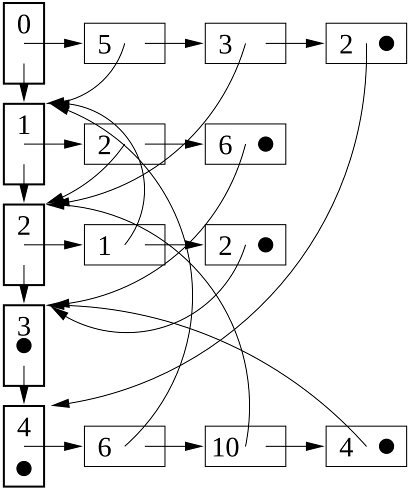

specific.h

```c
#define GRAPHTYPE "Linked"

#define INITSIZE 8
#define SCALEFACTOR 2

#define TMPSTR 1000

#define NO_VERT -1

typedef unsigned int edge;

struct vertex {
   char* label;
   struct vertex* nextv;
   void* firste;
   int num;
};
typedef struct vertex vertex;

struct edge {
   edge weight;
   vertex* v;
   struct edge* nexte;
};
typedef struct edge edgel;

struct graph {
   vertex* firstv;
   vertex* endv;
   int size;
};
typedef struct graph graph;
```

Linked II

```c
graph* graph_init(void)
{
   graph* g = (graph*) ncalloc(1, sizeof(graph));
   return g;
}

edge graph_getEdgeWeight(graph* g, int from, int to)
{
   if((g==NULL) || (from >= g->size) || (to >= g->size)){
      return INF;
   }
   vertex* v = g->firstv;
   for(int i=0; i<from; i++){
      v = v->nextv;
   }
   if((v==NULL) || (v->num != from)){
      return INF;
   }
   edgel* e = v->firste;
   while(e != NULL){
      if(e->v->num == to){
         return e->weight;
      }
      e = e->nexte;
   }
   return INF;
}
```

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   graph* g = (graph*) ncalloc(1, sizeof(graph));
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   if((g==NULL) || (from >= g->size) || (to >= g->size)){
      return INF;
   }
   vertex* v = g->firstv;
   for(int i=0; i<from; i++){
      v = v->nextv;
   }
   if((v==NULL) || (v->num != from)){
      return INF;
   }
   edgel* e = v->firste;
   while(e != NULL){
      if(e->v->num == to){
         return e->weight;
      }
      e = e->nexte;
   }
   return INF;
}
```

```c
bool graph_addEdge(graph* g, int from, int to, edge w)
{
   if((g==NULL) || (g->size == 0)){
      return false;
   }
   if((from >= g->size) || (to >= g->size)){
      return false;
   }
   vertex* f = g->firstv;
   for(int i=0; i<from; i++){
      f = f->nextv;
   }
   vertex* t = g->firstv;
   for(int i=0; i<to; i++){
      t = t->nextv;
   }
   return _addEdge(f, t, w);
}
```

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- A proof either way would have profound implications for mathematics, cryptography, AI etc.

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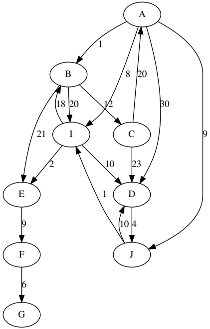
- `A -> B -> C -> D -> J -> I -> E -> F -> G`



TSP II

```
edge graph_salesman(graph* g, int from, char* str)
{
   bool* unvis;
   int curr, ncurr, nvs;
   edge cst, bcst, e;

   nvs = graph_numVerts(g);
   if((g==NULL) || (from >= nvs) || (str==NULL)){
      return INF;
   }
   unvis = (bool*)ncalloc(nvs, sizeof(bool));
   for(int v=0; v<nvs; v++){
      unvis[v] = true;
   }
   curr = from;
   bcst = 0;
   strcpy(str, graph_getLabel(g, from));
   do{
      unvis[curr] = false;
      cst = INF;
      ncurr = NO_VERT;
      /* Look at neighbours of curr */
```

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   strcpy(str, graph_getLabel(g, from));
   do{
      unvis[curr] = false;
      cst = INF;
      ncurr = NO_VERT;
      /* Look at neighbours of curr */
      for(int v=0; v<nvs; v++){
         e = graph_getEdgeWeight(g, curr, v);
         if((v!=curr) && unvis[v] && (e!=INF)){
            if(e < cst){
               cst = e;
               ncurr = v;
            }
         }
      }
      /* Add in cost to go to closest */
      if(cst < INF){
         bcst += cst;
         curr = ncurr;
         strcat(str, " ");
         strcat(str, graph_getLabel(g, ncurr));
      }
   }while((cst < INF) && (curr != NO_VERT));
   free(unvis);
   return bcst;
}
```

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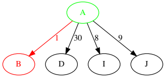

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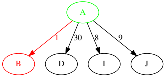

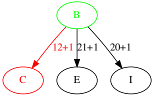

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