Chapitre 5: Structures de données

INF3135
Construction et maintenance de logiciels

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v253

Généralités

Structure de données

Organisation **logique** d'un ensemble de données

Plusieurs objectifs

- **Simplifier** le traitement
- Offrir des opérations **efficaces**
- Économiser de l'espace **mémoire**

Interface et implémentation

- **Interface**: opérations supportées (type abstrait)
- **Implémentation**: organisation des données en mémoire, actions effectuées pour réaliser les opérations

Type abstrait: exemples

- **Pile** (*stack*): principe *last in first out (LIFO)*
- **File** (*queue*): principe *first in first out (FIFO)*
- **File à priorité** (*priority queue*): la priorité des éléments peut être augmentée ou diminuée
- **Liste**: les éléments sont ordonnés, on peut avoir des opérations d'accès, d'insertion, de suppression
- **Ensemble** (*set*): aucune donnée répétée (doublon), vérification d'appartenance d'éléments, données ordonnées ou non
- **Tableau associatif** (*map*): un ensemble de paires clé-valeur, les clés doivent être uniques, les valeurs peuvent être répétées
- **Partition**: division d'un ensemble en parties, fusion entre parties, vérifier si deux éléments sont dans la même partie
- **Graphe**: relations symétriques (graphes non orientés) ou non symétrique (graphes orientés) entre entités

Implémentation: exemples

- **Tableau statique**: mémoire allouée et fixe, capacité maximale permise
- **Tableau dynamique**: tableau compressé ou allongé selon les besoins
- **Liste simplement chaînée**: chaque élément a une référence au suivant
- **Liste doublement chaînée**: chaque élément a une référence à l'élément précédent et à l'élément suivant
- **Structure arborescente**: arbres binaires, arbres préfixes, arbres suffixes, arbres d'arité quelconque, arbres coloriés, arbres-kd
- **Tableau multidimensionnel**: statiques ou dynamiques
- **Liste d'adjacence**: matrice creuse, graphes

Invariants et opérations

Invariant

- **Propriété** qui doit être satisfaite en tout temps
- Généralement vérifiable à l'aide d'une **fonction** booléenne

Opération

- Toute fonction qui **modifie** la structure de données
- Doit toujours préserver les **invariants**

Exemples

- **Chaîne de caractères**: termine par `'\0'`
- **Liste simplement chaînée**: le dernier noeud pointe vers `NULL`
- **Arbre binaire de recherche**: les clés respectent l'ordre

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Allocation dynamique

Allocation dynamique

- Jusqu'à maintenant: mémoire réservée de façon **statique**
- Or, cette information n'est **pas toujours connue** à l'avance
- **Solution**: allouer l'espace mémoire de façon **dynamique**
- Dans la bibliothèque `stdlib.h`:

```c
// Réserve un bloc de taille `size`
void* malloc(size_t size);
// Libère l'espace mémoire pointé par `ptr`
void free(void* ptr);
// Réserve un bloc de taille `nmemb * size` initialisé à 0
void* calloc(size_t nmemb, size_t size);
// Redimensionne un bloc de taille `size` déjà alloué dynamiquement
void* realloc(void* ptr, size_t size);
// Redimensionne un bloc de taille `nmemb * size`
void* reallocarray(void* ptr, size_t nmemb, size_t size);
```

Les fonctions `malloc` et `calloc`

```
void* malloc(size_t size);
```

- Réserve sur le **tas** (*heap*) un bloc de mémoire
- De **taille** `size`
- **Retourne** un pointeur vers ce bloc
- **Retourne** `NULL` s'il n'y a plus d'espace mémoire

```
void* calloc(size_t nmemb, size_t size);
```

- Réserve `nmemb` blocs de mémoire **consécutifs**
- De taille **individuelle** `size`
- **Initialise** toutes les valeurs à `0`
- **Retourne** un pointeur vers ce bloc
- **Retourne** `NULL` s'il n'y a plus d'espace mémoire

La fonction `free`

```c
void free(void* ptr);
```

- **Libère** l'espace mémoire pointé par `ptr`
- Réservé lors d'un appel **précédent** à `malloc` ou `calloc`
- La taille libérée est **égale** à celle réservée
- Si `ptr == NULL`, alors rien ne se passe

Attention

- Si `free` a déjà été appelé sur `ptr`
- Ou si la mémoire pointée par `ptr` n'a pas été allouée précédemment

Alors le comportement est **indéfini**.

Les fonctions `realloc` et `reallocarray`

```
void* realloc(void* ptr, size_t size);
```

- **Redimensionne** un bloc de mémoire à la taille `size`
- **Préalablement** réservé avec `malloc` ou `calloc`
- **Retourne** un pointeur vers le bloc redimensionné
- **Retourne** `NULL` s'il n'y a plus d'espace mémoire

```
void* reallocarray(void* ptr, size_t nmemb, size_t size);
```

- **Équivalent** à `realloc(ptr, nmemb * size)`

Attention

- La valeur des **octets** présents avant et après est **préservée**
- Si **agrandissement**, les « nouveaux » octets sont **indéterminés**
- Pointeur retourné peut être **différent** du pointeur en 1er argument

Gestion de la mémoire

Fuite de mémoire (*memory leak*)

- Mémoire **réservée** mais non **référencée**
- Provoquée lorsqu'on appelle `malloc` ou `calloc`
- Et qu'on oublie de libérer avec `free`
- **Attention**: souvent « cachée » derrière une autre fonction

Exemples

- Initialisation d'une **structure de données** dynamique
- Utilisation de la fonction `strdup` (duplication de chaîne)
- Bibliothèque SDL: `SDL_Init`

Comment les éviter?

- S'assurer que tout **appel** à `malloc` ou `calloc`
- Est **couplé** à un appel de la fonction `free`
- Souvent à l'aide de **fonctions**

Responsabilité de mémoire

- Si une fonction utilise `malloc` sans `free` associé
- Le comportement doit être **documenté** (*docstring*)
- **Exemple**: la fonction `strdup`
  The strdup() function returns a pointer to a new string which is a duplicate of the string s. Memory for the new string is obtained with malloc(3), and can be freed with free(3).

- Fournir une fonction **complémentaire** qui libère l'espace alloué
- **Exemple**: `SDL_Quit` est l'« inverse » de `SDL_Init`

Attention

- Pas de **ramasse-miettes** (*garbage collector*)
- Préférer un passage par **adresse**
- Et utiliser `malloc/calloc/free` seulement lorsqu'inévitable

L'outil Valgrind

- Cadriciel permettant de concevoir des outils d'**analyse dynamique**
- Permet de détecter des erreurs de **gestion de mémoire**
- Et de **profiler** un programme en détail
- **Lien officiel**: http://valgrind.org/
- **Invocation**:

```
$ valgrind [options valgrind] [programme] [options programme]
```

Plusieurs dizaines d'**options**:

- `--tool=<toolname>`: outil (par défaut, `memcheck`)
- `--leak-check=<no|summary|yes|full>`: vérifier fuites mémoires
- `--time-stamp=<yes|no>`: afficher chronologie
- `--track-origins=<yes|no>`: origine des valeurs non initialisées
- etc.

Exemple (1/5)

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

double* sum(const double* v1, const double* v2, unsigned int n) {
  double* v = malloc(n * sizeof(double));
  for (unsigned int i = 0; i < n; ++i)
    v[i] = v1[i] + v2[i];
  return v;
}

void print_vector(const double* v, unsigned int n) {
  printf("[ ");
  for (unsigned int i = 0; i < n; ++i)
    printf("%lf ", v[i]);
  printf("]");
}

int main(void) {
  double v1[] = { 2.0, -1.5,  3.4};
  double v2[] = {-1.0,  2.1, -0.8};
  print_vector(sum(v1, v2, 3), 3);
  return 0;
}
```

Résultat:

```
[ 1.000000 0.600000 2.600000 ]
```

Exemple (2/5)

```
$ gcc sum_malloc.c -o sum_malloc
$ valgrind ./sum_malloc
$ valgrind --leak-check=yes ./sum_malloc
==6724== Memcheck, a memory error detector
==6724== Copyright (C) 2002-2017, and GNU GPL'd, by Julian Seward et al.
==6724== Using Valgrind-3.13.0 and LibVEX; rerun with -h for copyright info
==6724== Command: ./sum_malloc
==6724==
[ 1.000000 0.600000 2.600000 ]==6724==
==6724== HEAP SUMMARY:
==6724==     in use at exit: 24 bytes in 1 blocks
==6724==   total heap usage: 2 allocs, 1 frees, 1,048 bytes allocated
==6724==
==6724== 24 bytes in 1 blocks are definitely lost in loss record 1 of 1
==6724==    at 0x4C2FB0F: malloc (in /usr/lib/valgrind/[...]
==6724==    by 0x10876B: sum (in [...]/code/sum_malloc)
==6724==    by 0x1088BE: main (in [...]/code/sum_malloc)
==6724==
==6724== LEAK SUMMARY:
==6724==    definitely lost: 24 bytes in 1 blocks
==6724==    indirectly lost: 0 bytes in 0 blocks
==6724==      possibly lost: 0 bytes in 0 blocks
==6724==    still reachable: 0 bytes in 0 blocks
==6724==         suppressed: 0 bytes in 0 blocks
==6724==
==6724== For counts of detected and suppressed errors, rerun with: -v
==6724== ERROR SUMMARY: 1 errors from 1 contexts (suppressed: 0 from 0)
```

Exemple (3/5)

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

double* sum(const double* v1, const double* v2, unsigned int n) {
  double* v = malloc(n * sizeof(double));
  for (unsigned int i = 0; i < n; ++i)
    v[i] = v1[i] + v2[i];
  return v;
}

void print_vector(const double* v, unsigned int n) {
  printf("[ ");
  for (unsigned int i = 0; i < n; ++i)
    printf("%lf ", v[i]);
  printf("]");
}

int main(void) {
  double v1[] = { 2.0, -1.5,  3.4};
  double v2[] = {-1.0,  2.1, -0.8};
  double* v = sum(v1, v2, 3);
  print_vector(v, 3);
  free(v);
  return 0;
}
```

Exemple (4/5)

```
$ gcc sum_malloc_free.c -o sum_malloc_free
$ valgrind --leak-check=yes ./sum_malloc_free
==10376== Memcheck, a memory error detector
==10376== Copyright (C) 2002-2017, and GNU GPL'd, by Julian Seward et al.
==10376== Using Valgrind-3.13.0 and LibVEX; rerun with -h for copyright info
==10376== Command: ./sum_malloc_free
==10376==
[ 1.000000 0.600000 2.600000 ]
==10376==
==10376== HEAP SUMMARY:
==10376==     in use at exit: 0 bytes in 0 blocks
==10376==   total heap usage: 2 allocs, 2 frees, 1,048 bytes allocated
==10376==
==10376== All heap blocks were freed -- no leaks are possible
==10376==
==10376== For counts of detected and suppressed errors, rerun with: -v
==10376== ERROR SUMMARY: 0 errors from 0 contexts (suppressed: 0 from 0)
```

Allocation dynamique

- Est-ce que `malloc` est vraiment nécessaire ici?
- **Réponse**: non!

Exemple (5/5)

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

void compute_sum(const double* v1, const double* v2,
                 double* v, unsigned int n) {
  for (unsigned int i = 0; i < n; ++i)
      v[i] = v1[i] + v2[i];
}

void print_vector(const double* v, unsigned int n) {
  printf("[ ");
  for (unsigned int i = 0; i < n; ++i)
    printf("%lf ", v[i]);
  printf("]");
}

int main(void) {
  double v1[] = { 2.0, -1.5,  3.4};
  double v2[] = {-1.0,  2.1, -0.8};
  double v[3];
  compute_sum(v1, v2, v, 3);
  print_vector(v, 3);
  return 0;
}
```

Piles

Pile

- Structure de donnée **fondamentale**
- Stratégie *LIFO* = *last in first out*

Interface minimale (pile de caractères)

```
// Initialize the stack
void stack_initialize(Stack* s);
// Is stack empty?
bool stack_is_empty(const Stack* s);
// Push a value on top
void stack_push(Stack* s, char value);
// Pop the value from the top
char stack_pop(Stack* s);
// Delete a stack
void stack_delete(Stack* s);
```

Implémentation

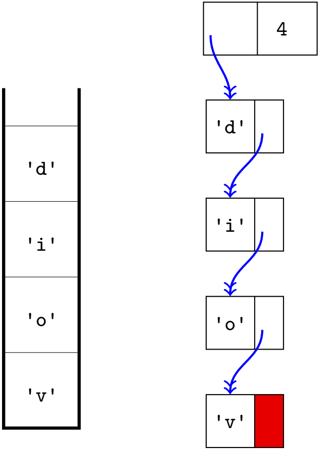
- **Tableau** statique ou dynamique
- Liste **simplement chaînée**

Représentation

Déclaration de types en C:

```c
// Node
struct StackNode {
  char value;
  struct StackNode* next;
};

// Stack
typedef struct {
  struct StackNode* first;
  unsigned int size;
} Stack;
```

Représentation schématique:



Invariants

Trois invariants

Pour toute **pile** `s` et pour tout **noeud** `node` de `s`,

- `node.next == NULL` **ssi** `node` est le dernier noeud de `s`
- `s.first == NULL` **ssi** `stack_is_empty(s)` est *vrai*
- Le nombre de noeuds dans `s` est donné par `s.size`

Utilité?

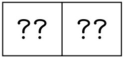
- Quand on implémente `stack_push` et `stack_pop`
- **Supposer** les invariants satisfaits en **début de fonction**
- Et s'assurer qu'ils sont encore satisfaits à la **fin**

Implémentation (1/2)

```c
// Initialize the stack
void stack_initialize(Stack* s) {
  s->first = NULL;
  s->size = 0;
}

// Is stack empty?
bool stack_is_empty(const Stack* s) {
  return s->size == 0;
}

// Push a value on top
void stack_push(Stack* s, char value) {
  struct StackNode* node = malloc(sizeof(struct StackNode));
  node->value = value;
  node->next = s->first;
  s->first = node;
  ++s->size;
}
```


Implémentation (1/2)

```c
// Initialize the stack
void stack_initialize(Stack* s) {
  s->first = NULL;
  s->size = 0;
}

// Is stack empty?
bool stack_is_empty(const Stack* s) {
  return s->size == 0;
}

// Push a value on top
void stack_push(Stack* s, char value) {
  struct StackNode* node = malloc(sizeof(struct StackNode));
  node->value = value;
  node->next = s->first;
  s->first = node;
  ++s->size;
}
```



Implémentation (1/2)

```c
// Initialize the stack
void stack_initialize(Stack* s) {
  s->first = NULL;
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void stack_push(Stack* s, char value) {
  struct StackNode* node = malloc(sizeof(struct StackNode));
  node->value = value;
  node->next = s->first;
  s->first = node;
  ++s->size;
}
```

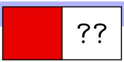

Implémentation (1/2)

```c
// Initialize the stack
void stack_initialize(Stack* s) {
  s->first = NULL;
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void stack_push(Stack* s, char value) {
  struct StackNode* node = malloc(sizeof(struct StackNode));
  node->value = value;
  node->next = s->first;
  s->first = node;
  ++s->size;
}
```

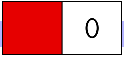

Implémentation (1/2)

```c
// Initialize the stack
void stack_initialize(Stack* s) {
  s->first = NULL;
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}

// Is stack empty?
bool stack_is_empty(const Stack* s) {
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void stack_push(Stack* s, char value) {
  struct StackNode* node = malloc(sizeof(struct StackNode));
  node->value = value;
  node->next = s->first;
  s->first = node;
  ++s->size;
}
```

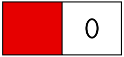

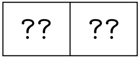

Implémentation (1/2)

```c
// Initialize the stack
void stack_initialize(Stack* s) {
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void stack_push(Stack* s, char value) {
  struct StackNode* node = malloc(sizeof(struct StackNode));
  node->value = value;
  node->next = s->first;
  s->first = node;
  ++s->size;
}
```
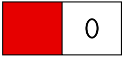
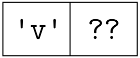
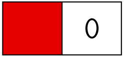



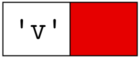


Implémentation (1/2)

```c
// Initialize the stack
void stack_initialize(Stack* s) {
  s->first = NULL;
  s->size = 0;
}
```




```c
// Is stack empty?
bool stack_is_empty(const Stack* s) {
  return s->size == 0;
}
```




```c
// Push a value on top
void stack_push(Stack* s, char value) {
  struct StackNode* node = malloc(sizeof(struct StackNode));
  node->value = value;
  node->next = s->first;
  s->first = node;
  ++s->size;
}
```

Implémentation (1/2)

```c
// Initialize the stack
void stack_initialize(Stack* s) {
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// Is stack empty?
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// Push a value on top
void stack_push(Stack* s, char value) {
  struct StackNode* node = malloc(sizeof(struct StackNode));
  node->value = value;
  node->next = s->first;
  s->first = node;
  ++s->size;
}
```
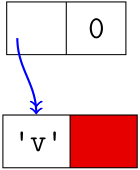
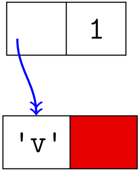



Implémentation (1/2)

```c
// Initialize the stack
void stack_initialize(Stack* s) {
  s->first = NULL;
  s->size = 0;
}

// Is stack empty?
bool stack_is_empty(const Stack* s) {
  return s->size == 0;
}

// Push a value on top
void stack_push(Stack* s, char value) {
  struct StackNode* node = malloc(sizeof(struct StackNode));
  node->value = value;
  node->next = s->first;
  s->first = node;
  ++s->size;
}
```



Implémentation (2/2)

```c
// Pop the value from the top
char stack_pop(Stack* s) {
  if (!stack_is_empty(s)) {
    char value = s->first->value;
    struct StackNode* node = s->first;
    s->first = node->next;
    free(node);
    --s->size;
    return value;
  } else {
    fprintf(stderr, "Cannot pop from empty stack\n");
    exit(1);
    return '?';
  }
}

// Delete a stack
void stack_delete(Stack* s) {
  while (!stack_is_empty(s)) stack_pop(s);
}
```

Exemple d'utilisation: parenthésage équilibré

```c
/**
 * Returns true if and only if an expression is balanced
 *
 * @param expr   The expression to check
 * @returns      True if and only if the expression is balanced
 */
bool is_balanced(const char* expr) {
  bool balanced = true;
  Stack s;
  stack_initialize(&s);
  for (unsigned int i = 0; balanced && expr[i] != '\0'; ++i) {
    if (expr[i] == '(') {
      stack_push(&s, ')');
    } else if (expr[i] == '[') {
      stack_push(&s, ']');
    } else if (expr[i] == '{') {
      stack_push(&s, '}');
    } else if (expr[i] == ')' || expr[i] == ']' || expr[i] == '}') {
      if (stack_is_empty(&s))
        balanced = false;
      else
        balanced = expr[i] == stack_pop(&s);
    }
  }
  balanced = balanced && stack_is_empty(&s);
  stack_delete(&s);
  return balanced;
}
```

Tableaux dynamiques

Tableau dynamique

- Tableau dont la taille **varie** selon l'usage
- Supporté **par défaut** dans plusieurs langages
- **Exemples**: C++ (`vector`), Java (`ArrayList`), Python (listes)

Implémentation

- **Capacité** (*capacity*): taille « réelle » du tableau en mémoire
- **Taille** (*size*): nombre d'éléments « pertinents »

Redimensionnement

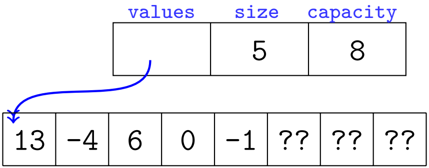
- **Automatiquement**, en doublant la taille
- Ou **manuellement**, par un appel de fonction
- Parfois, **contracté** automatiquement quand trop d'espace inoccupé

Interface

```
// Initialize an empty array
void array_initialize(Array* a);

// Append an element to the end of an array
void array_append(Array* a, int e);

// Insert an element in an array
void array_insert(Array* a, unsigned int i, int element);

// Remove an element from an array at a given index
void array_remove(Array* a, unsigned int i);

// Check if an array contains a given element
bool array_has_element(const Array* a, int e);

// Return the element at a given index in an array
int array_get(const Array* a, unsigned int i);

// Delete an array
void array_delete(Array* a);
```

Représentation

```c
// A resizable array
typedef struct {
  int* values;          // The values of the array
  unsigned int size;    // The current size
  unsigned int capacity; // The capacity
} Array;
```



Invariants:

- La taille réservée par `values` est `capacity * sizeof(int)`
- `size <= capacity`
- Seules les `size` premières valeurs sont « pertinentes »

Implémentation (1/4)

```c
// Initialize an empty array
void array_initialize(Array* a) {
  a->values = malloc(sizeof(int));
  a->size = 0;
  a->capacity = 1;
}

// Append an element to the end of an array
void array_append(Array* a, int e) {
  array_resize_if_needed(a);
  a->values[a->size] = e;
  ++a->size;
}

// Insert an element in an array
void array_insert(Array* a, unsigned int i, int e) {
  array_check_index(a, i);
  array_resize_if_needed(a);
  for (unsigned int j = a->size - 1; j > i; --j)
    a->values[j] = a->values[j - 1];
  a->values[i] = e;
  ++a->size;
}
```

Implémentation (2/4)

```c
// Remove an element from an array at a given index
void array_remove(Array* a, unsigned int i) {
  array_check_index(a, i);
  ++i;
  while (i < a->size) {
    a->values[i - 1] = a->values[i];
    ++i;
  }
  --a->size;
}

// Check if an array contains a given element
bool array_has_element(const Array* a, int e) {
  unsigned int i = 0;
  while (i < a->size && array_unsafe_get(a, i) != e)
     ++i;
  return i < a->size;
}
```

Implémentation (3/4)

```c
// Return the element at a given index in an array
int array_get(const Array* a, unsigned int i) {
  array_check_index(a, i);
  return array_unsafe_get(a, i);
}

// Delete an array
void array_delete(Array* a) {
  free(a->values);
}

// Resize an array if the capacity is reached
void array_resize_if_needed(Array* a) {
  if (a->size == a->capacity) {
    a->capacity *= 2;
    a->values = realloc(a->values, a->capacity * sizeof(int));
  }
}
```

Implémentation (4/4)

```c
// Return the element at index i in an array (no check)
int array_unsafe_get(const Array* a, unsigned int i) {
  return a->values[i];
}

// Print an array to stdout
void array_print(const Array* a) {
  unsigned int i;
  printf("[");
  for (i = 0; i < a->size; ++i) {
    printf(" %d", a->values[i]);
  }
  printf(" ]");
}

// Check if an index is out of bound
void array_check_index(const Array* a, unsigned int i) {
  if (i >= a->size) {
    fprintf(stderr, "Invalid index %d (size = %d)\n", i, a->size);
    exit(1);
  }
}
```

Utilisation (1/2)

```
int main() {
  Array a; array_initialize(&a);
  printf("Appending 3, 2, 5, 7, 8, 7: ");
  array_append(&a, 3); array_append(&a, 2);
  array_append(&a, 5); array_append(&a, 7);
  array_append(&a, 8); array_append(&a, 7);
  array_print(&a);
  printf("\nRemoving at position 2: ");
  array_remove(&a, 2); array_print(&a);
  printf("\nRemoving at position 4: ");
  array_remove(&a, 4); array_print(&a);
  printf("\nRemoving at position 2: ");
  array_remove(&a, 2); array_print(&a);
  printf("\nInserting 7 at position 1: ");
  array_insert(&a, 1, 7); array_print(&a);
  printf("\n");
  for (int e = 0; e <= 9; e += 2)
    printf("Has element %d ? %s\n", e,
           array_has_element(&a, e) ? "yes" : "no");
  array_delete(&a);
}
```

Utilisation (2/2)

Résultat:

```
Appending 3, 2, 5, 7, 8, 7: [ 3 2 5 7 8 7 ]
Removing at position 2: [ 3 2 7 8 7 ]
Removing at position 4: [ 3 2 7 8 ]
Removing at position 2: [ 3 2 8 ]
Inserting 7 at position 1: [ 3 7 2 8 ]
Has element 0 ? no
Has element 2 ? yes
Has element 4 ? no
Has element 6 ? no
Has element 8 ? yes
```

Tableaux multidimensionnels

Tableau multidimensionnel

- Généralisation d'un tableau à **plusieurs dimensions**
- Aussi appelé **matrice**
- Simplifie la manipulation des **données** homogènes
- En les organisant selon leurs **dimensions**

Version aplatie

- Tableau **unidimensionnel**
- **Plus** compact
- Mais on doit gérer l'**accès** (indexation)

Par indirection

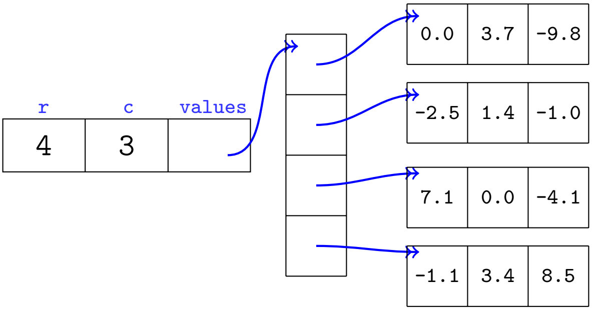
- Tableau de **pointeurs**
- **Moins** compact
- Mais plus facile de gérer l'indexation

Interface (partielle)

```c
// Initialize a matrix
void matrix_initialize(struct Matrix* m,
                       unsigned int r,
                       unsigned int c,
                       bool random);

// Print a matrix to stdout
void matrix_print(const struct Matrix* m);

// Add the matrix `m2` to the matrix `m1`
void matrix_add(struct Matrix* m1, const struct Matrix* m2);

// Delete the given matrix
void matrix_delete(struct Matrix* m);
```

Représentation

```c
struct Matrix {
  unsigned int r;   // Number of rows
  unsigned int c;   // Number of columns
  double** values; // Values in matrix
};
```



Implémentation (1/3)

```c
// Initialize a matrix with 0 or random values
void matrix_initialize(struct Matrix* m,
                       unsigned int r,
                       unsigned int c,
                       bool random) {
  m->r = r;
  m->c = c;
  m->values = malloc(r * sizeof(double*));
  for (unsigned int i = 0; i < r; ++i) {
    m->values[i] = malloc(c * sizeof(double));
    for (unsigned int j = 0; j < c; ++j) {
      if (random)
        m->values[i][j] = (float)rand() /
                          (float)(RAND_MAX / 20.0) - 10.0;
      else
        m->values[i][j] = 0.0;
    }
  }
}
```

Implémentation (2/3)

```c
// Print a matrix to stdout
void matrix_print(const struct Matrix* m) {
  for (unsigned int i = 0; i < m->r; ++i) {
    printf("[ ");
    for (unsigned int j = 0; j < m->c; ++j)
      printf("%6.2lf ", m->values[i][j]);
    printf("]\n");
  }
}

// Add the second matrix to the first one
void matrix_add(struct Matrix* m1, const struct Matrix* m2) {
  if (m1->r != m2->r || m1->c != m2->c) {
    fprintf(stderr, "Error: matrices have different dimensions\n");
    exit(1);
  }
  for (unsigned int i = 0; i < m1->r; ++i)
    for (unsigned int j = 0; j < m1->c; ++j)
      m1->values[i][j] += m2->values[i][j];

}
```

Implémentation (3/3)

```c
// Delete a matrix
void matrix_delete(struct Matrix* m) {
  for (unsigned int i = 0; i < m->r; ++i)
    free(m->values[i]);
  free(m->values);
}
```

Utilisation (1/2)

```c
int main(void) {
  srand(time(NULL));
  struct Matrix m1, m2;
  printf("Initializing m1:\n");
  matrix_initialize(&m1, 3, 5, true);
  matrix_print(&m1);
  printf("Initializing m2:\n");
  matrix_initialize(&m2, 3, 5, true);
  matrix_print(&m2);
  printf("Adding m2 to m1:\n");
  matrix_add(&m1, &m2); matrix_print(&m1);
  matrix_delete(&m1); matrix_delete(&m2);
  return 0;
}
```

Utilisation (2/2)

Résultat (les valeurs peuvent varier):

```
Initializing m1:
[   7.07   9.70  -6.46  -4.45   1.04 ]
[  -5.21  -1.31  -6.26  -8.26   0.70 ]
[   1.93  -8.22  -0.17  -8.96   8.88 ]
Initializing m2:
[  -0.74   1.29   1.24  -8.09  -3.17 ]
[  -1.95  -6.93  -2.18   1.96  -4.75 ]
[   4.34   3.63   0.78  -5.20   7.19 ]
Adding m2 to m1:
[   6.33  10.99  -5.22 -12.54  -2.14 ]
[  -7.15  -8.24  -8.44  -6.30  -4.05 ]
[   6.26  -4.59   0.61 -14.16  16.07 ]
```

Arbres binaires de recherche

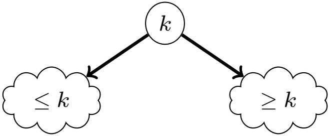
Arbres binaires de recherche

Arbre binaire

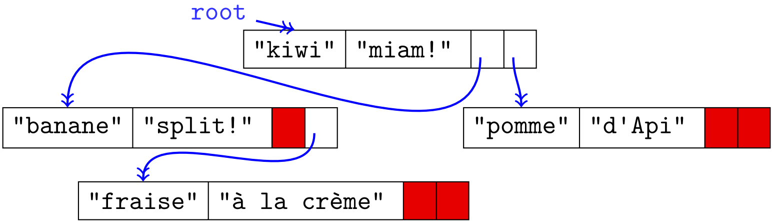
- Ensemble de noeuds organisés de façon **hiérarchique**
- Chaque noeud référence **deux** enfants
- Possiblement **vides**

Arbre binaire de recherche (ABR)

- Chaque noeud est identifié par une **clé**
- Choisie dans un ensemble de clés **totalement ordonné**
- Et contient une **valeur**
- **Invariant**:



Représentation




```c
// A tree node
struct TreeNode {
  char* key;                // Key
  char* value;              // Value
  struct TreeNode* left;    // Left subtree
  struct TreeNode* right;   // Right subtree
};

// A tree map
typedef struct {
  struct TreeNode* root; // Root of tree
} Treemap;
```

Interface

```c
// Initialize an empty tree map
void treemap_initialize(Treemap* t);

// Return the value associated with the given key in a tree map
char* treemap_get(const Treemap* t, const char* key);

// Set the value for the given key in a tree map
void treemap_set(Treemap* t, const char* key, const char* value);

// Indicate if a key exists in a tree map
bool treemap_has_key(const Treemap* t, const char* key);

// Print a tree map to stdout
void treemap_print(const Treemap* t);

// Delete a tree map
void treemap_delete(Treemap* t);
```

Récupérer un noeud

```c
struct TreeNode* treemap_get_node(const struct TreeNode* node,
                                  const char* key) {
  if (node == NULL) {
    return NULL;
  } else {
    int cmp = strcmp(key, node->key);
    if (cmp == 0)
      return (struct TreeNode*)node;
    else if (cmp < 0)
      return treemap_get_node(node->left, key);
    else
      return treemap_get_node(node->right, key);
  }
}
```

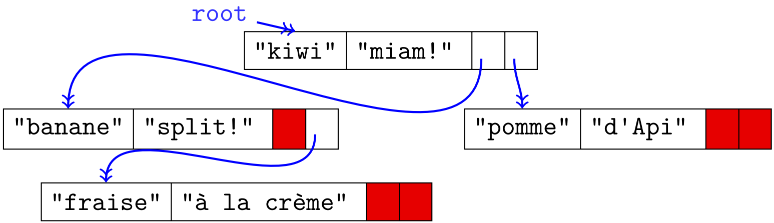
Insérer un noeud

```c
void treemap_insert_node(struct TreeNode** node,
                         const char* key,
                         const char* value) {
    if (*node == NULL) {
        *node = malloc(sizeof(struct TreeNode));
        (*node)->key = strdup(key);
        (*node)->value = strdup(value);
        (*node)->left = NULL;
        (*node)->right = NULL;
    } else if (strcmp(key, (*node)->key) < 0) {
        treemap_insert_node(&(*node)->left, key, value);
    } else {
        treemap_insert_node(&(*node)->right, key, value);
    }
}
```

Insérer un noeud

```c
void treemap_insert_node(struct TreeNode** node,
                         const char* key,
                         const char* value) {
    if (*node == NULL) {
        *node = malloc(sizeof(struct TreeNode));
        (*node)->key = strdup(key);
        (*node)->value = strdup(value);
        (*node)->left = NULL;
        (*node)->right = NULL;
    } else if (strcmp(key, (*node)->key) < 0) {
        treemap_insert_node(&(*node)->left, key,
    } else {
        treemap_insert_node(&(*node)->right, key, va
    }
}
```

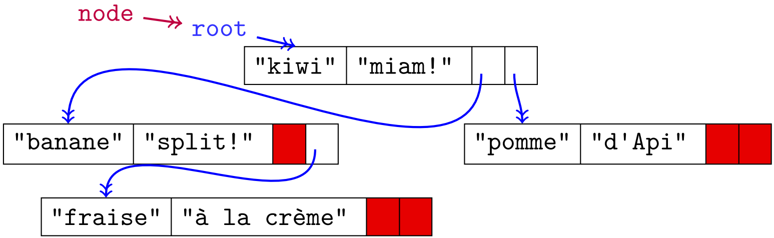
On souhaite insérer
la clé melon



Insérer un noeud

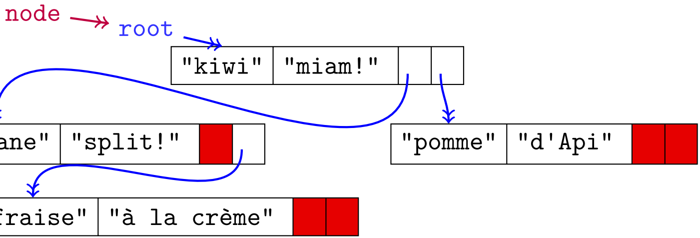
```c
void treemap_insert_node(struct TreeNode** node,
                         const char* key,
                         const char* value) {
    if (*node == NULL) {
        *node = malloc(sizeof(struct TreeNode));
        (*node)->key = strdup(key);
        (*node)->value = strdup(value);
        (*node)->left = NULL;
        (*node)->right = NULL;
    } else if (strcmp(key, (*node)->key) < 0) {
        treemap_insert_node(&(*node)->left, key,
    } else {
        treemap_insert_node(&(*node)->right, key, va
    }
}
```

On souhaite insérer la clé melon



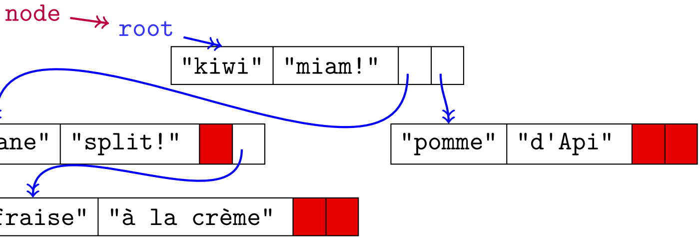
Insérer un noeud

```c
void treemap_insert_node(struct TreeNode** node,
                         const char* key,
                         const char* value) {
    if (*node == NULL) {
        *node = malloc(sizeof(struct TreeNode));
        (*node)->key = strdup(key);
        (*node)->value = strdup(value);
        (*node)->left = NULL;
        (*node)->right = NULL;
    } else if (strcmp(key, (*node)->key) < 0) {
        treemap_insert_node(&(*node)->left, key, value);
    } else {
        treemap_insert_node(&(*node)->right, key, value);
    }
}
```



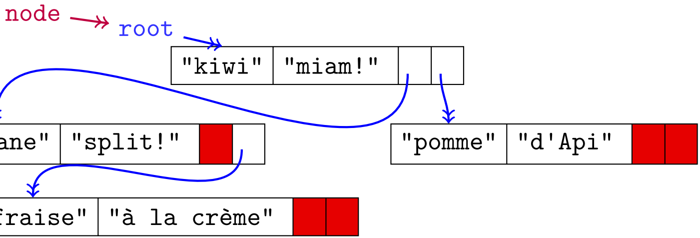
Insérer un noeud

```c
void treemap_insert_node(struct TreeNode** node,
                         const char* key,
                         const char* value) {
    if (*node == NULL) {
        *node = malloc(sizeof(struct TreeNode));
        (*node)->key = strdup(key);
        (*node)->value = strdup(value);
        (*node)->left = NULL;
        (*node)->right = NULL;
    } else if (strcmp(key, (*node)->key) < 0) {
        treemap_insert_node(&(*node)->left, key, value);
    } else {
        treemap_insert_node(&(*node)->right, key, value);
    }
}
```



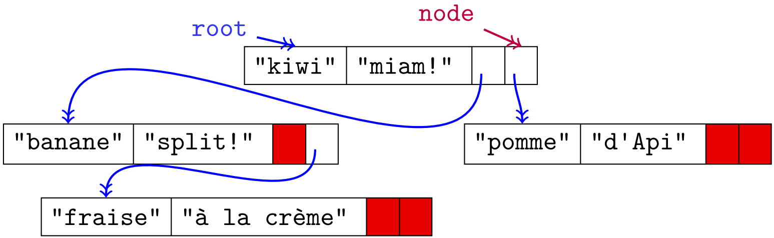
Insérer un noeud

```
void treemap_insert_node(struct TreeNode** node,
                         const char* key,
                         const char* value) {
    if (*node == NULL) {
        *node = malloc(sizeof(struct TreeNode));
        (*node)->key = strdup(key);
        (*node)->value = strdup(value);
        (*node)->left = NULL;
        (*node)->right = NULL;
    } else if (strcmp(key, (*node)->key) < 0) {
        treemap_insert_node(&(*node)->left, key, value);
    } else {
        treemap_insert_node(&(*node)->right, key, value);
    }
}
```



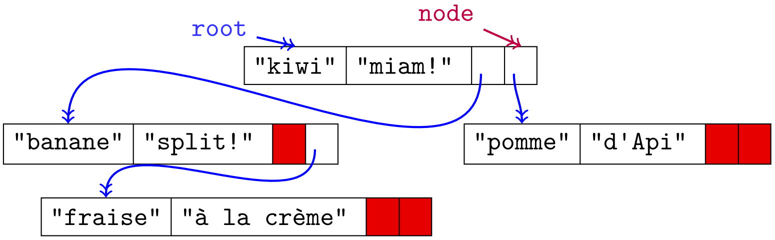
Insérer un noeud

```c
void treemap_insert_node(struct TreeNode** node,
                         const char* key,
                         const char* value) {
    if (*node == NULL) {
        *node = malloc(sizeof(struct TreeNode));
        (*node)->key = strdup(key);
        (*node)->value = strdup(value);
        (*node)->left = NULL;
        (*node)->right = NULL;
    } else if (strcmp(key, (*node)->key) < 0) {
        treemap_insert_node(&(*node)->left, key, value);
    } else {
        treemap_insert_node(&(*node)->right, key, value);
    }
}
```



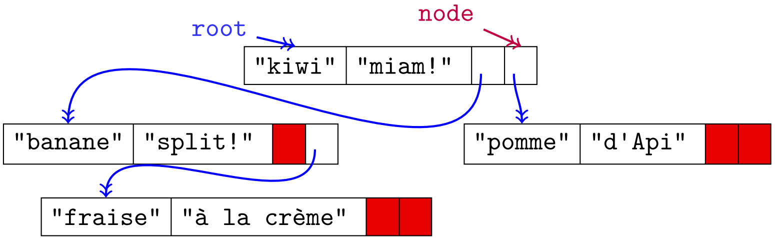
Insérer un noeud

```c
void treemap_insert_node(struct TreeNode** node,
                         const char* key,
                         const char* value) {
    if (*node == NULL) {
        *node = malloc(sizeof(struct TreeNode));
        (*node)->key = strdup(key);
        (*node)->value = strdup(value);
        (*node)->left = NULL;
        (*node)->right = NULL;
    } else if (strcmp(key, (*node)->key) < 0) {
        treemap_insert_node(&(*node)->left, key, value);
    } else {
        treemap_insert_node(&(*node)->right, key, value);
    }
}
```



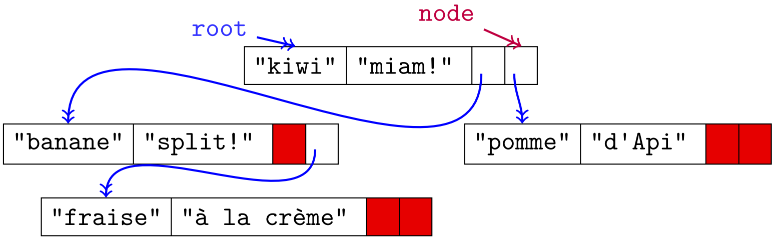
Insérer un noeud

```
void treemap_insert_node(struct TreeNode** node,
                         const char* key,
                         const char* value) {
    if (*node == NULL) {
        *node = malloc(sizeof(struct TreeNode));
        (*node)->key = strdup(key);
        (*node)->value = strdup(value);
        (*node)->left = NULL;
        (*node)->right = NULL;
    } else if (strcmp(key, (*node)->key) < 0) {
        treemap_insert_node(&(*node)->left, key, value);
    } else {
        treemap_insert_node(&(*node)->right, key, value);
    }
}
```



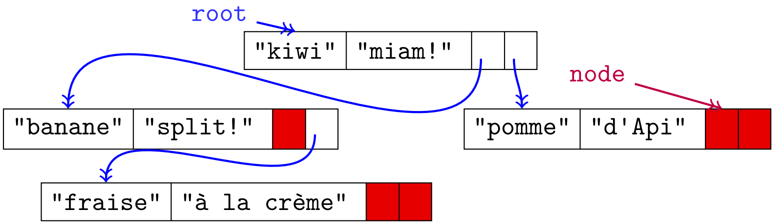
Insérer un noeud

```
void treemap_insert_node(struct TreeNode** node,
                         const char* key,
                         const char* value) {
    if (*node == NULL) {
        *node = malloc(sizeof(struct TreeNode));
        (*node)->key = strdup(key);
        (*node)->value = strdup(value);
        (*node)->left = NULL;
        (*node)->right = NULL;
    } else if (strcmp(key, (*node)->key) < 0) {
        treemap_insert_node(&(*node)->left, key, value);
    } else {
        treemap_insert_node(&(*node)->right, key, value);
    }
}
```



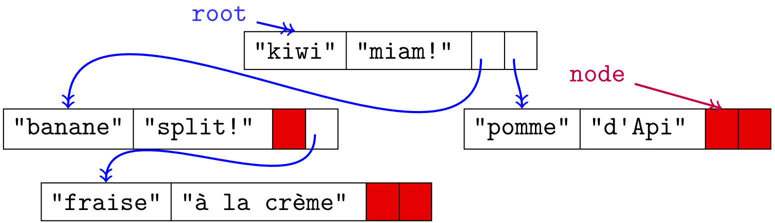
Insérer un noeud

```
void treemap_insert_node(struct TreeNode** node,
                         const char* key,
                         const char* value) {
    if (*node == NULL) {
        *node = malloc(sizeof(struct TreeNode));
        (*node)->key = strdup(key);
        (*node)->value = strdup(value);
        (*node)->left = NULL;
        (*node)->right = NULL;
    } else if (strcmp(key, (*node)->key) < 0) {
        treemap_insert_node(&(*node)->left, key, value);
    } else {
        treemap_insert_node(&(*node)->right, key, value);
    }
}
```



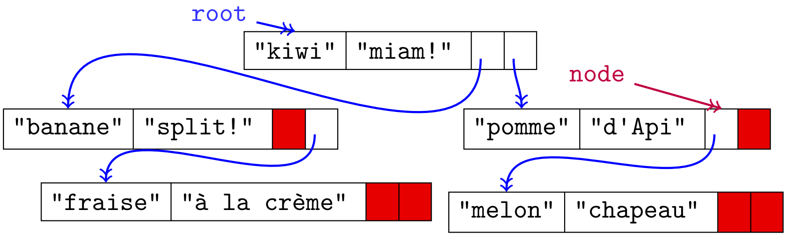
Insérer un noeud

```c
void treemap_insert_node(struct TreeNode** node,
                         const char* key,
                         const char* value) {
    if (*node == NULL) {
        *node = malloc(sizeof(struct TreeNode));
        (*node)->key = strdup(key);
        (*node)->value = strdup(value);
        (*node)->left = NULL;
        (*node)->right = NULL;
    } else if (strcmp(key, (*node)->key) < 0) {
        treemap_insert_node(&(*node)->left, key, value);
    } else {
        treemap_insert_node(&(*node)->right, key, value);
    }
}
```



Insérer un noeud

```c
void treemap_insert_node(struct TreeNode** node,
                         const char* key,
                         const char* value) {
    if (*node == NULL) {
        *node = malloc(sizeof(struct TreeNode));
        (*node)->key = strdup(key);
        (*node)->value = strdup(value);
        (*node)->left = NULL;
        (*node)->right = NULL;
    } else if (strcmp(key, (*node)->key) < 0) {
        treemap_insert_node(&(*node)->left, key, value);
    } else {
        treemap_insert_node(&(*node)->right, key, value);
    }
}
```



Implémentation (1/3)

```c
void treemap_initialize(Treemap* t) {
  t->root = NULL;
}

char* treemap_get(const Treemap* t, const char* key) {
  struct TreeNode* node = treemap_get_node(t->root, key);
  return node == NULL ? NULL : node->value;
}

bool treemap_has_key(const Treemap* t, const char* key) {
  return treemap_get_node(t->root, key) != NULL;
}

void treemap_set(Treemap* t, const char* key, const char* value) {
  struct TreeNode* node = treemap_get_node(t->root, key);
  if (node != NULL) {
    free(node->value);
    node->value = strdup(value);
  } else {
    treemap_insert_node(&(t->root), key, value);
  }
}
```

Implémentation (2/3)

```c
void treemap_print(const Treemap* t) {
  printf("TreeMap {\n");
  treemap_print_node(t->root);
  printf("}\n");
}

void treemap_print_node(const struct TreeNode* node) {
  if (node != NULL) {
    treemap_print_node(node->left);
    printf("  %s: %s\n", node->key, node->value);
    treemap_print_node(node->right);
  }
}
```

Implémentation (2/3)

```c
void treemap_delete(Treemap* t) {
  treemap_delete_node(t->root);
}

void treemap_delete_node(struct TreeNode* node) {
  if (node != NULL) {
    treemap_delete_node(node->left);
    treemap_delete_node(node->right);
    free(node->key);
    free(node->value);
    free(node);
  }
}
```

Utilisation (1/2)

```c
int main() {
  Treemap t;
  treemap_initialize(&t);
  treemap_set(&t, "firstname", "Doina");
  treemap_set(&t, "lastname", "Precup");
  treemap_set(&t, "city", "Montreal");
  treemap_set(&t, "province", "Quebec");
  treemap_set(&t, "country", "Canada");
  treemap_set(&t, "position", "DeepMind");
  printf("Printing the tree map\n");
  treemap_print(&t);
  printf("Get \"firstname\": %s\n", treemap_get(&t, "firstname"));
  printf("Get \"province\": %s\n", treemap_get(&t, "province"));
  printf("Get \"position\": %s\n", treemap_get(&t, "position"));
  printf("Changing country to Romania\n");
  treemap_set(&t, "country", "Romania");
  printf("Get \"country\": %s\n", treemap_get(&t, "country"));
  printf("Printing the tree map\n"); treemap_print(&t);
  treemap_delete(&t);
}
```

Utilisation (2/2)

Résultat:

```
Printing the tree map
TreeMap {
  city: Montreal
  country: Canada
  firstname: Doina
  lastname: Precup
  position: DeepMind Montreal Head
  province: Quebec
}
Get "firstname": Doina
Get "province": Quebec
Get "position": DeepMind Montreal Head
Changing country to Romania
Get "country": Romania
Printing the tree map
TreeMap {
  city: Montreal
  country: Romania
  firstname: Doina
  lastname: Precup
  position: DeepMind Montreal Head
  province: Quebec
}
```