Abstract Data Types (ADTs)
Design & Generic Implementations

Optional Textbook Readings: CP:AMA 19.5, 17.7 (qsort)

The primary goals of this section are to be able to use choose appropriate data structures and/or ADTs for a given situation, and to write generic ADTs.

Selecting a data structure

In Computer Science, every data structure is some combination of the following “core” data structures.

- primitives (e.g., an int)
- structures (i.e., struct)
- arrays
- linked lists
- trees
- graphs

Selecting an appropriate data structure is important in program design. Consider a situation where you are choosing between an array, a linked list, and a BST. Some design considerations are:

- How frequently will you add items? remove items?
- How frequently will you search for items?
- Do you need to access an item at a specific position?
- Do you need to preserve the “original sequence” of the data, or can it be re-arranged?
- Can you have duplicate items?

Knowing the answers to these questions and the efficiency of each data structure function will help you make design decisions.
Sequenced data

Consider the following strings to be stored in a data structure.

"Wei" "Jenny" "Ali"

Is the original sequencing important?

- If it's the result of a competition, yes: "Wei" is in first place.
  We call this type of data sequenced.
- If it's a list of friends to invite to a party, it is not important.
  We call this type of data unsequenced or “rearrangeable”.

If the data is sequenced, then a data structure that sorts the data (e.g., a BST) is likely not an appropriate choice. Arrays and linked lists are better suited for sequenced data.

Data structure comparison: sequenced data

<table>
<thead>
<tr>
<th>Function</th>
<th>Dynamic Array</th>
<th>Linked List</th>
</tr>
</thead>
<tbody>
<tr>
<td>item_at</td>
<td>$O(1)$</td>
<td>$O(n)$</td>
</tr>
<tr>
<td>search</td>
<td>$O(n)$</td>
<td>$O(n)$</td>
</tr>
<tr>
<td>insert_at</td>
<td>$O(n)$</td>
<td>$O(n)$</td>
</tr>
<tr>
<td>insert_front</td>
<td>$O(n)$</td>
<td>$O(1)$</td>
</tr>
<tr>
<td>insert_back</td>
<td>$O(1)^*$</td>
<td>$O(1)^+$</td>
</tr>
<tr>
<td>remove_at</td>
<td>$O(n)$</td>
<td>$O(n)$</td>
</tr>
<tr>
<td>remove_front</td>
<td>$O(n)$</td>
<td>$O(1)$</td>
</tr>
<tr>
<td>remove_back</td>
<td>$O(1)$</td>
<td>$O(1)^*$</td>
</tr>
</tbody>
</table>

* amortized
† requires a back pointer – $O(n)$ without
⋄ requires a doubly linked list and a back pointer – $O(n)$ without.

Data structure comparison: unsequenced (sorted) data

<table>
<thead>
<tr>
<th>Function</th>
<th>Sorted Dynamic</th>
<th>Sorted Linked</th>
<th>Self-Balancing Unbalanced</th>
<th>Self-Balancing BST</th>
</tr>
</thead>
<tbody>
<tr>
<td>search</td>
<td>$O(\log n)$</td>
<td>$O(n)$</td>
<td>$O(n)$</td>
<td>$O(\log n)$</td>
</tr>
<tr>
<td>insert</td>
<td>$O(n)$</td>
<td>$O(n)$</td>
<td>$O(n)$</td>
<td>$O(\log n)$</td>
</tr>
<tr>
<td>remove</td>
<td>$O(n)$</td>
<td>$O(n)$</td>
<td>$O(n)$</td>
<td>$O(\log n)$</td>
</tr>
<tr>
<td>select</td>
<td>$O(1)$</td>
<td>$O(n)$</td>
<td>$O(n)$</td>
<td>$O(\log n)^+$</td>
</tr>
</tbody>
</table>

† requires a count augmentation – $O(n)$ without.

select(k) finds the item with index $k$ in the structure.
For example, select(0) finds the smallest element.
example: design decisions

• An array is a good choice if you frequently access elements at specific positions (random access).

• A linked list is a good choice for sequenced data if you frequently add and remove elements at the start.

• A self-balancing BST is a good choice for unsequenced data if you frequently search for, add and remove items.

• A sorted array is a good choice if you rarely add/remove elements, but frequently search for elements and select the data in sorted order.

Implementing collection ADTs

A significant benefit of a collection ADT is that a client can use it “abstractly” without worrying about how it is implemented.

In practice, ADT modules are usually well-written, optimized and have a well documented interface.

In this course, we are interested in how to implement ADTs.

Typically, the collection ADTs are implemented as follows.

• Stack: linked lists or dynamic arrays

• Queue: linked lists

• Sequence: linked lists or dynamic arrays.
  Some libraries provide two different ADTs (e.g., a list and a vector) that provide the same interface but have different operation run-times.

• Dictionary (and Sets): self-balanced BSTs or hash tables*.

* A hash table is typically an array of linked lists (more on hash tables in CS 240).
Beyond integers

In Section 10, we implemented a Stack ADT that stores \texttt{int} items.

What if we want a stack that stores a different \textit{type} of item?

We could write a separate implementation for each possible item type, but that is unwieldy.

It would be nice if we could develop a "generic" ADT that can store “any” type.

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We don't have this problem in Racket because of dynamic typing.

This is one reason why Racket and other dynamic typing languages are so popular.

Some statically typed languages have a \textit{template} feature to avoid this problem. For example, in C++ a stack of integers is defined as:

```cpp
stack<int> my_int_stack ;
```

The stack ADT (called a stack “container”) is built-in to the C++ STL (standard template library).

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\textbf{void pointers}

The \texttt{void} pointer (\texttt{void \*}) is the closest C has to a “generic” type.

\texttt{void} pointers can store the address of (“point at”) \textit{any} type of data.

```c
int i = 42;
int \*pi = \&i;
struct posn p = {3, 4};

void \*vp = NULL;
vp = \&i;
vp = \&p;
vp = \&pi;
vp = \&vp;
```

\textit{void} pointers can not point at functions.
Dereferencing void pointers

void pointers can not be dereferenced.

```c
int i = 42;
void *vp = &i;

int j = *vp; // INVALID
*vp = 13;    // INVALID
int k = vp[0]; // INVALID
```

Do not confuse void functions (that return “nothing”) and void pointers (that can point at “anything”).

They are unrelated concepts that share a keyword.

Assigning from void pointers

void pointers can not be dereferenced.

However, the address stored in a void pointer can be assigned to the correct type of pointer variable and then be dereferenced.

This is why malloc works for any type of data (its return type is a void pointer).

```c
int i = 42;
void *vp = &i; // vp points at an int
int *ip = vp;   // OK
int j = *ip;
*ip = 13;
```

Caution with void pointers

When assigning from void pointers, we lose type safety and could have a pointer pointing to the wrong type. Dereferencing such a pointer causes undefined and potentially dangerous behaviour.

```c
int i = 42;
void *vp = &i; // vp points at an int
struct posn *pp = vp; // BAD (but allowed by C)
int j = pp->y; // BAD (undefined behaviour)
pp->y = 13; // BAD (undefined behaviour)
```

You should only assign from a void pointer when you are sure that the pointer variable is the correct type for the data at that address.

If void pointers are potentially unsafe, why are they used?
Generic functions

With `void` pointers, we can now write functions that operate on any type of data.

For example, the `qsort` function is part of `<stdlib.h>` and can sort an array of any type (in ascending order).

```c
void qsort(void * arr, int len, size_t size,
           int (*compare)(const void * , const void * ));
```

The parameters are:

- an array, its length and the size of each element (in bytes)
- a function to compare elements

Generic comparison function

The comparison function required by `qsort` follows the same convention as `strcmp`.

In other words, `compare(a, b)` returns:

- a negative `int` if `*a` precedes `*b`
- zero if `*a` and `*b` are equal.
- a positive `int` if `*a` follows `*b`

If you reverse the above behaviour, then `qsort` will sort an array in descending order.

Example: `qsort` with ints

```c
// requires: a, b point at ints
int compare_ints(const void * a, const void * b) {
    const int *ia = a;
    const int *ib = b;
    return *ia - *ib;
}

int main(void) {
    int a[7] = {8, 6, 7, 5, 3, 0, 9};
    print_array(a, 7);
    qsort(a, 7, sizeof(int), compare_ints);
    print_array(a, 7);
}
```

```plaintext
8, 6, 7, 5, 3, 0, 9.
0, 3, 5, 6, 7, 8, 9.
```
More generic functions

<stdlib.h> also provides a generic binary search (bsearch) that either returns a pointer to the key in the sorted array if found, or NULL if not found.

```c
void *bsearch(const void *key,
              const void *arr, int len, size_t size,
              int (*compare)(const void *, const void *));
```

Another useful function is memcpy in <string.h> which simply copies size bytes from a source to a destination.

```c
void *memcpy(void *dest, const void *src, size_t size);
```

**memcpy** returns the destination for historical reasons.

Generic map function

In Section 07, we wrote an int map function but now we can write a generic version.

The only challenge is finding the address of each element (arr[i]). Because a char is only one byte, we can “pretend” the array is a char array, and then perform the pointer arithmetic manually.

```c
void generic_map(void *arr, int len, size_t size,
                 void (*map_function)(void *)) {
    char *arr_base = arr;
    for (int i = 0; i < len; ++i) {
        map_function(arr_base + i * size);
    }
}
```
Generic ADTs with void pointers

We can now create generic container ADTs that can store “any” type of data by storing void pointers.

For example, we can modify our stack ADT from Section 10 to store void pointer items (instead of ints).

This requires only a few minor changes to the code.

As we will discuss shortly, the only significant change is the behaviour of stack_destroy, which now requires the stack to be empty.

example: generic stack

Very little code has changed (indicated by //!).
Previously, we used an array of `int`s. Now, we want an array of `void` pointers:

```c
struct int_stack {
    int len;
    int maxlen;
    int *data;  // OLD
};

struct stack {
    int len;
    int maxlen;
    void **data;  // NEW
};
```

A "`void *"" pointer is generic and can point at "anything".

A "`void **"" pointer is not generic: it is a pointer to a "`void *"", and can be dereferenced and behave like an array (of `void` pointers).

```c
struct stack * stack_create(void) {
    struct stack * s = malloc(sizeof(struct stack));
    s->len = 0;
    s->maxlen = 1;
    s->data = malloc(s->maxlen * sizeof(void *));  //!
    return s;
}

// requires: s is empty  //!
void stack_destroy(struct stack *s) {
    assert(stack_is_empty(s));  //!
    free(s->data);
    free(s);
}

bool stack_is_empty(const struct stack *s) {
    return s->len == 0;
}
```

```c
void stack_push(void *item, struct stack *s) {  //!
    if (s->len == s->maxlen) {
        s->maxlen *= 2;
        s->data = realloc(s->data, s->maxlen * sizeof(void *));  //!
    }
    s->data[s->len] = item;
    s->len += 1;
}
```

```c
const void * stack_top(const struct stack *s) {  //!
    assert(!stack_is_empty(s));
    return s->data[s->len - 1];
}
```

```c
void * stack_pop(struct stack *s) {  //!
    assert(!stack_is_empty(s));
    s->len -= 1;
    return s->data[s->len];
}
```
// this reads in strings ("words") and then prints them
// out in reverse order.

int main(void) {
    struct stack *s = stack_create();
    while(1) {
        char *str = read_str();  // from Sec 10
        if (!str) {
            break;
        }
        stack_push(str, s);
    }
    while(!stack_is_empty(s)) {
        char *str = stack_pop(s);
        printf("%s\n", str);
        free(str);
    }
    stack_destroy(s);
}

Memory management with generic ADTs

A generic ADT does not "know" the type of the items it stores, and
so it does not "know" the type of memory those items are using.

For example, each item could be a pointer to:

- non-heap memory (e.g., a string literal)
- a heap allocation (e.g., a dynamically allocated array)
- a structure with multiple dynamic elements (e.g., a linked list)

Consequently, the ADT can not perform any memory management
on its items (e.g., the ADT can not naïvely free an item).

For our generic stack ADT, we avoided the memory management
issue by requiring the stack to be empty before it is destroyed.

This means the client is responsible for freeing all of the items.

If we did not add this requirement, destroying the stack would cause
a memory leak if the items use dynamic memory.

Alternatively, we could design the stack ADT so the client has to
provide a free function (that appropriately frees an item).
// store pointer to the free function in the ADT structure

struct stack {
    int len;
    int maxlen;
    void **data;
    void (*free_item)(void *); // function pointer
};

// client provides free function when stack is created

struct stack *stack_create(void (*free_function)(void *)) {
    struct stack *s = malloc(sizeof(struct stack));
    s->len = 0;
    s->maxlen = 1;
    s->data = malloc(s->maxlen * sizeof(void *));
    s->free_item = free_function;
    return s;
}

// note: no longer requires stack to be empty

void stack_destroy(struct stack *s) {
    for (int i = 0; i < s->len; ++i) { // free all of
        s->free_item(s->data[i]);  // the items
    }
    free(s->data);
    free(s);
}

The client can provide an appropriate free function.

    // for non-heap memory (e.g., string literals)
void free_nothing(void *item) { } // do nothing

    // for dynamic arrays
void free_single_allocation(void *item) {
    free(item);
}

    // for data types with multiple dynamic elements
void free_linked_list(void *item) {
    list_destroy(item);
}

Client communication

For a simple stack ADT, a free function is unwarranted. Requiring
an empty stack before destruction is a reasonable approach.

For other ADTs, it may be necessary. For example, a dictionary ADT
might require two free functions (for keys and values).

Other ADTs may have operations that copy (or “duplicate”) items,
and require a copy function.

It is important to make a clear interface to communicate to the
client how the memory for the individual items will be managed.
Comparison functions

Many ADTs need a comparison function to compare items and possibly sort items.

For example, a dictionary ADT must be able to compare keys to perform a lookup operation.

Typically, comparison functions use the same convention as strcmp (and qsort).

As with the earlier example (providing a free function to the stack ADT), a comparison function pointer can be provided when the ADT is created and stored in the ADT structure.

### Example: Dictionary ADT with Comparison Function

```c
struct dictionary {
    // ...
    int (*key_compare)(const void *, const void *); // func ptr
};

const void *dict_lookup(const void *key, const struct dictionary *d) {
    const struct bstnode *node = d->root;
    while (node) {
        int result = d->key_compare(key, node->item);
        if (result == 0) return node->value;
        if (result < 0) {
            node = node->left;
        } else {
            node = node->right;
        }
    }
    return NULL;
}
```

Alternatives to C

We have reached our final core learning goal: making generic ADTs in C with void pointers. Much of the course content has been leading up to this point.

However, it seems appropriate to mention that C is not the most suitable language for working with generic ADTs. C is a very powerful language, but it is sometimes inconvenient and inflexible.

There are many other languages that are easier to work with and have better support for information hiding, abstraction, modularization, dynamic types, garbage collection, etc.
It may surprise you to know that the Racket language interpreter is written in C (it is available on Github).

How is it possible that Racket uses dynamic typing? (and garbage collection and ints that do not overflow, and . . .)

Consider this (simplified) C representation of a Racket object:

```c
struct racket_object {
    int type; // int = 1, string = 2, list = 3, etc.
    void *data;
}
```

Each object has an int to identify the type and a void pointer to the data. Built-in Racket functions simply check the type and then process the data accordingly.

In practice, you may see C code that casts void pointers.

*Casting* explicitly “forces” a *type conversion* by placing the destination type in parentheses to the left of an expression.

C does not require void pointers to be cast but C++ does, which is why it is often seen in practice.

A useful application of casting is to avoid integer division when working with floats or doubles (see CP:AMA 7.4).

Here are a few examples of casting:

```c
double one_half = ((double) 1) / 2;
int *a = (int *) malloc(n * sizeof(int));
void *vp = (void *) a;
*(int *)vp = 136;
```

**Goals of this Section**

At the end of this section, you should be able to:

- determine an appropriate data structure and/or ADT for a given design problem
- implement a generic function with void pointers
- implement generic ADTs using comparison and memory management functions
- describe the memory management issues related to using void pointers in ADTs