The material for this lecture is drawn, in part, from The Practice of Programming (Kernighan & Pike) Chapter 4
Goals of this Lecture

Help you learn:

• How to create high quality modules in C

Why?

• Abstraction is a powerful (the only?) technique available for understanding large, complex systems
• A mature programmer knows how to find the abstractions in a large program
• A mature programmer knows how to convey a large program’s abstractions via its modularity
A good module:

- Encapsulates data
- Manages resources
- Is consistent
- Has a minimal interface
- Detects and handles/reports errors
- Establishes contracts
- Has strong cohesion
- Has weak coupling
Encapsulation + Information Hiding

A well-designed module encapsulates data
  • An interface should hide implementation details
  • A module should not allow clients to manipulate the data directly
  • A module should use its functions to encapsulate its data

Why?
  • **Clarity**: Encourages abstraction
  • **Security**: Clients cannot corrupt object by changing its data in unintended ways
  • **Flexibility**: Allows implementation to change – even the underlying representation, e.g. data structure – without affecting clients
"An abstract data type defines a class of abstract objects which is completely characterized by the operations available on those objects. This means that an abstract data type can be defined by defining the characterizing operations for that type."


Turing Award winner 2008:
“For contributions to practical and theoretical foundations of programming language and system design, especially related to data abstraction, fault tolerance, and distributed computing.”
Abstract Data Type (ADT)

A **data type** has a representation:

```c
struct Node {  
  int key;  
  struct Node *next;  
};
struct List {  
  struct Node *first;  
};
```

and some operations:

```c
struct List *new()  
{  
  struct List *p;  
  p = calloc(1, sizeof(*p));  
  assert(p != NULL);  
  return p;  
}
void insert(struct List *p, int key)  
{  
  struct Node *n;  
  n = malloc(sizeof(*n));  
  assert(n != NULL);  
  n->key=key; n->next=p->first; p->first=n;  
}
```

An **abstract data type** has a hidden representation; all client code must access the type through its *interface*:

```c
struct List;  
struct List *new();  
void insert(struct List *p, int key);  
void concat(struct List *p, struct List *q);  
int nth_key(struct List *p, int n);  
...  
```
Encapsulation with ADTs (wrong!)

list.h

```c
struct Node {int key; struct Node *next;};
struct List {struct Node *first;};

struct List *new();
void insert(struct List *p, int key);
void concat(struct List *p, struct List *q);
int nth_key(struct List *p, int n);
```

client.c

```c
#include "list.h"

int f(void) {
    struct List *p, *q;
    p = new();
    q = new();
    insert(p,6);
    insert(p,7);
    insert(q,5);
    concat(p,q);
    concat(q,p);
    return nth_key(q,1);
}
```

diagram-

list_linked.c

```c
#include "list.h"

struct List *new()
{
    struct List *p;
    p = calloc(1, sizeof(*p));
    assert(p != NULL);
    return p;
}

void insert(struct List *p, int key) {...}
void concat(struct List *p, *q) { ... }
int nth_key(struct List *p, int n) { ... }
```
Encapsulation with ADTs (right!)

**list.h**

```c
struct List;

struct List *new();
void insert(struct List *p, int key);
void concat(struct List *p,
           struct List *q);
int nth_key(struct List *p, int n);
```

**list_linked.c**

```c
#include "list.h"

struct Node {int key; struct Node *next;};
struct List {struct Node *first;};

struct List *new() {
    struct List *p;
    p = calloc(1, sizeof(*p));
    assert(p != NULL);
    return p;
}

void insert(struct List *p, int key) {...}
void concat(struct List *p, *q) { ... }
int nth_key(struct List *p, int n) { ... }
```

Including only the declaration in header file enforces the abstraction: it keeps clients from accessing fields of the struct, allowing implementation to change.
If you can’t see the representation (or the implementations of `insert`, `concat`, `nth_key`), then how are you supposed to know what they do?

**Specification:**

A List $p$ represents a sequence of integers $\sigma$.

- **Operation `new()`**: returns a list $p$ representing the empty sequence.
- **Operation `insert(p, i)`**: if $p$ represents $\sigma$, causes $p$ to now represent $i \cdot \sigma$.
- **Operation `concat(p, q)`**: if $p$ represents $\sigma_1$ and $q$ represents $\sigma_2$, causes $p$ to represent $\sigma_1 \cdot \sigma_2$ and leaves $q$ representing $\sigma_2$.
- **Operation `nth_key(p, n)`**: if $p$ represents $\sigma_1 \cdot i \cdot \sigma_2$ where the length of $\sigma_1$ is $n$, returns $i$ otherwise (if the length of the string represented by $p$ is $\leq n$), it returns an arbitrary integer.

```c
struct List;
struct List *new();
void insert(struct list *p, int key);
void concat(struct list *p,
            struct list *q);
int nth_key(struct list *p, int n);
```

This is OK! Client programs relying on unspecified behavior might break with a new implementation.
Reasoning About Client Code

List of specifications allows for reasoning about the effects of client code.

```c
int f(void) {
    struct List *p, *q;
    p = new();
    q = new();
    insert (p,6);
    insert (p,7);
    insert (q,5);
    concat (p,q);
    concat (q,p);
    return nth_key(q,1);
}
```

```c
struct List;
struct List * new(void);
void insert(struct list *p, int key);
void concat(struct list *p,
    struct list *q);
int nth_key(struct list *p, int n);
```
C is not inherently an object-oriented language, but can use language features to encourage object-oriented thinking.

- Interface provides `List_T` abbreviation for client
  - Interface encourages client to think of **objects** (not structures) and **object references** (not pointers to structures)
  - Client still cannot access data directly: data is “opaque” to client

```c
typedef struct List *List_T;

List_T new();
void insert(List_T p, int key);
void concat(List_T p, List_T q);
int nth_key(List_T p, int n);
```

"Opaque" pointer type
Q: Is a string, as used by the `<string.h>` module an ADT?

A. Yes – clients can’t see the implementation of `strcpy`, etc.

B. Yes – clients can’t see the representation of strings.

C. No – clients can see the implementation of `strcpy`, etc.

D. No – clients can see the representation of strings.  
   We know the underlying representation of strings.

D

E. No – strings are not a datatype.  
   Clients can manipulate the string’s state directly, not through the interface.
Living with ADTs

Sometimes need to provide controlled access to internal representation

- For example, what if we want to be able to print contents of a List_T?
- Or perform some other operation on the keys?
- Do we have to define every possible operation in list.h?
Function Pointers

Sometimes need to provide controlled access to internal representation

Function pointers to the rescue:

```c
/* list.h */
void foreach(List_T p, void (*func)(int key));

/* list_linked.c */
void foreach_node(struct Node *n, void (*func)(int key))
{
    if (!n)
        return;
    (*func)(n->key);
    foreach_node(n->next, func);
}

void foreach(List_T p, void (*func)(int key))
{
    foreach_node(p->first, func);
}

/* main.c */
void print_int(int i)
{
    printf("%d\n", i);
}

int main()
{
    List_T p = new();
    insert(p, 42);
    insert(p, 78);
    foreach(p, &print_int);
}
```
Function Pointers

Shortcut notation for function pointers:
(the only time in C that you can be sloppy and omit & and *)

```c
/* list.h */
void foreach(List_T p, void func(int key));

/* list_linked.c */
void foreach_node(struct Node *n, void func(int key))
{
    if (!n)
        return;
    func(n->key);
    foreach_node(n->next, func);
}

void foreach(List_T p, void func(int key))
{
    foreach_node(p->first, func);
}
```

```c
/* main.c */
void print_int(int i)
{
    printf("%d\n", i);
}

int main()
{
    List_T p = new();
    insert(p, 42);
    insert(p, 78);
    foreach(p, print_int);
}
```
A good module:

- Encapsulates data
- **Manages resources**
- Is consistent
- Has a minimal interface
- Detects and handles/reports errors
- Establishes contracts
- Has strong cohesion
- Has weak coupling
Resource Management

A well-designed module manages resources consistently

- A module should free a resource if and only if the module has allocated that resource
- Examples
  - Object allocates memory ⇔ object frees memory
  - Object opens file ⇔ object closes file

Why?

- Allocating and freeing resources at different levels is error-prone
  - Forget to free memory ⇒ memory leak
  - Forget to allocate memory ⇒ dangling pointer, seg fault
  - Forget to close file ⇒ inefficient use of a limited resource
  - Forget to open file ⇒ dangling pointer, seg fault
Who allocates and frees the key strings in symbol table?

Reasonable options:

(1) Client allocates and frees strings
   • SymTable_put() does not create copy of given string
   • SymTable_remove() does not free the string
   • SymTable_free() does not free remaining strings

(2) SymTable object allocates and frees strings
   • SymTable_put() creates copy of given string
   • SymTable_remove() frees the string
   • SymTable_free() frees all remaining strings

Our choice: (2)
   • With option (1) client could corrupt the SymTable object
     (as described in a previous lecture)
Who allocates and frees the values in symbol table?

Reasonable (?) options:

(1) Client allocates and frees values
   - SymTable_put() does not create copy of given value, yet client can’t corrupt data structure.
   - SymTable_remove() does not free the value
   - SymTable_free() does not free remaining values

(2) SymTable object allocates and frees values
   - SymTable_put() needs more parameters: the size of the value and a function pointer to a function that will copy the value (or to use memcpy, or to do an awful hack and cast the value to a char* and copy byte-by-byte)

   - SymTable_remove() frees the value
   - SymTable_free() frees all remaining values

Our choice: (1) simpler interface, no search integrity risk, no copy cost
Passing Resource Ownership

Violations of expected resource ownership should be noted explicitly in function comments

```c
somefile.h
...

/* ...
   This function allocates memory for
   the returned object. You (the caller)
   own that memory, and so are responsible
   for freeing it when you no longer
   need it. */

void *f();
...
```
Agenda

A good module:

- Encapsulates data
- Manages resources
- **Is consistent**
- Has a minimal interface
- Detects and handles/reports errors
- Establishes contracts
- Has strong cohesion
- Has weak coupling
A well-designed module is consistent

• A function's name should indicate its module
  • Facilitates maintenance programming
    • Programmer can find functions more quickly
  • Reduces likelihood of name collisions
    • From different programmers, different software vendors, etc.

• A module's functions should use a consistent parameter order
  • Facilitates writing client code
Consistency in `string.h`

Are function names consistent?

```c
/* string.h */

size_t strlen(const char *s);
char *strcpy(char *dest, const char *src);
char *strncpy(char *dest, const char *src, size_t n);
char *strcat(char *dest, const char *src);
char *strncat(char *dest, const char *src, size_t n);
int strcmp(const char *s1, const char *s2);
int strncmp(const char *s1, const char *s2, size_t n);
char *strstr(const char *haystack, const char *needle);
void *memcpy(void *dest, const void *src, size_t n);
int memcmp(const void *s1, const void *s2, size_t n);
...
```

Is parameter order consistent?
Consistency in symtable.h

Are function names consistent?

SymTable_T SymTable_new(void);
void SymTable_free(SymTable_T oSymTable);
size_t SymTable_getLength(SymTable_T oSymTable);
int SymTable_put(SymTable_T oSymTable, const char *pcKey, const void *pvValue);
void *SymTable_replace(SymTable_T oSymTable, const char *pcKey,
                      const void *pvValue);
int SymTable_contains(SymTable_T oSymTable, const char *pcKey);
void *SymTable_get(SymTable_T oSymTable, const char *pcKey);
void *SymTable_remove(SymTable_T oSymTable, const char *pcKey);
void SymTable_map(SymTable_T oSymTable,
                  void (*pfApply)(const char *pcKey, void *pvValue, void *pvExtra),
                  const void *pvExtra);

Is parameter order consistent?
Let’s make List accord ...

List

(−) Each function name begins with “List_”
(+ ) First parameter identifies List object

```c
typedef struct List *List_T;
List_T List_new();
void List_insert(List_T p, int key);
void List_concat(List_T p, List_T q);
int List_nth_key(List_T p, int n);
void List_free(List_T p);
```

List (revised)

(+) Each function name begins with “List_”
(+ ) First parameter identifies List object
A good module:

- Encapsulates data
- Manages resources
- Is consistent
- **Has a minimal interface**
- Detects and handles/reports errors
- Establishes contracts
- Has strong cohesion
- Has weak coupling
A well-designed module has a minimal interface

- Function declaration should be in a module's interface if and only if:
  - The function is necessary for functionality, or
  - The function is necessary for clarity of client code

Why?

- More functions $\Rightarrow$ higher learning costs, higher maintenance costs
SymTable\_contains\(\text{redundancy}\)?

Q: Assignment 3's interface has both \texttt{SymTable\_get()} (which returns NULL if the key is not found) and \texttt{SymTable\_contains()} – is the latter necessary?

A. No – should be eliminated  
B. Yes – necessary for functionality  
C. Yes – necessary for efficiency  
D. Yes – necessary for clarity

B  
SymTable bindings can have NULL values, but \texttt{SymTable\_get()} can’t tell these apart from keys that aren’t in the table.
Q: Assignment 3 has `SymTable_hash()` defined in `symtablehash.c`'s implementation, but not the `symtable.h` interface. Is this good design?

A. No – should be in interface to enable functionality

B. No – should be in interface to enable clarity

C. Yes – should remain an implementation detail

It is only ever used internally, and only in a hash table implementation.
A good module:

- Encapsulates data
- Manages resources
- Is consistent
- Has a minimal interface
- Detects and handles/reports errors
- Establishes contracts
- Has strong cohesion
- Has weak coupling
A well-designed module detects and handles/reports errors

A module should:

• **Detect** errors
• **Handle** errors if it can; otherwise...
• **Report** errors to its clients
  • A module often cannot assume what error-handling action its clients prefer
Handling Errors in C

C options for **detecting** errors
- if statement
- assert macro

C options for **handling** errors
- Write message to stderr
  - Impossible in many embedded applications
- Recover and proceed
  - Sometimes impossible
- Abort process
  - Often undesirable
C options for **reporting** errors to client (calling function)

- Use `function return value`?

```c
int div(int dividend, int divisor, int *quotient)
{
    if (divisor == 0)
        return 0;
    ...
    *quotient = dividend / divisor;
    return 1;
}
...
successful = div(5, 3, &quo);
if (!successful)
    /* Handle the error */
```

Awkward if return value has some other natural purpose
Reporting Errors in C

C options for **reporting** errors to client (calling function)

- Set **global variable**?

```c
int successful;
...
int div(int dividend, int divisor)
{
    if (divisor == 0) {
        successful = 0;
        return 0;
    }
    successful = 1;
    return dividend / divisor;
}
...
quo = div(5, 3);
if (!successful)
    /* Handle the error */
```

- Easy for client to forget to check
- Bad for multi-threaded programming
- Some standard C library functions set `errno` global variable 😞
C options for **reporting** errors to client (calling function)

- Use **call-by-reference** parameter?

```c
int div(int dividend, int divisor, int *successful) {
    if (divisor == 0) {
        *successful = 0;
        return 0;
    }
    *successful = 1;
    return dividend / divisor;
}
...
quo = div(5, 3, &successful);
if (!successful)
    /* Handle the error */
```

Awkward for client; must pass additional argument
C options for reporting errors to client (calling function)

- Call `assert` macro?

```c
int div(int dividend, int divisor)
{
    assert(divisor != 0);
    return dividend / divisor;
}
...
quo = div(5, 3);
```

- Asserts could be disabled
- Error terminates the process!
C options for **reporting** errors to client (calling function)

- No option is ideal

What option does Java provide?
User Errors

Our recommendation: Distinguish between...

(1) **User** errors

- Errors made by human user
- Errors that “could happen”

  - Example: Bad data in stdin
  - Example: Too much data in stdin
  - Example: Bad value of command-line argument

- Use if statement to detect
- Handle immediately if possible, or...
- Report to client via return value or call-by-reference parameter
  - Don’t use global variables
(2) **Programmer** errors

- Errors made by a programmer
- Errors that “should never happen”

- Example: pointer parameter should not be `NULL`, but is

- For now, use `assert` to detect and handle

The distinction sometimes is unclear

- Example: Write to file fails because disk is full
- Example: Divisor argument to `div()` is 0

Default: user error
Error Handling in List

- This error-handling in `List_insert` violates our advice just now.
- How to fix it? Some choices:
  - `void List_insert (List_T p, int key, int *error);`
  - `int List_insert (list_T p, int key);`
typedef struct List *List_T;

List_T List_new();
void List_insert(List_T p, int key);
void List_concat(List_T p, List_T q);
int List_nth_key(List_T p, int n);
void List_free(List_T p);

• And what about the curious specification for List_nth_key
• How to do better? Some choices:
  • int List_nth_key (List_T p, int n, int *success);
  • Or, perhaps more consistent with other bad parameter handling,  
    add the interface function int List_length(List_T p); then:
    Operation nth_key(p,n): if p represents $\sigma_1\cdot i\cdot \sigma_2$ where the length of $\sigma_1$ is n, returns i;  
    otherwise (if the length of the string represented by p is $\leq n$), it fails with an assertion failure or abort( ).
A good module:

- Encapsulates data
- Manages resources
- Is consistent
- Has a minimal interface
- Detects and handles/reports errors
  - Establishes contracts
  - Has strong cohesion
  - Has weak coupling
Establishing Contracts

A well-designed module establishes contracts

- A module should establish contracts with its clients
- Contracts should describe what each function does, especially:
  - Meanings of parameters
  - Work performed
  - Meaning of return value
  - Side effects

Why?

- Facilitates cooperation between multiple programmers
- Assigns blame to contract violators!!!
  - If your functions have precise contracts and implement them correctly, then the bug must be in someone else’s code!!!

How? Comments in module interface
Contracts in List

Comment defines contract:

- Meaning of function’s parameters
  - p is the list to be operated on; n is the index of an element
- Obligations of caller
  - make sure n is in range; (implicit) make sure p is a valid list
- Work performed
  - Return the nth element.
- Meaning of return value
- Side effects (none, by default)
Contracts in List

Comment defines contract:

- Meaning of function’s parameters
  - p is the list to be queried; n is the index of an element; success is an error flag
- Obligations of caller
  - (implicit) make sure p is a valid List
- Work performed
  - Return the nth element; set success appropriately
- Meaning of return value
- Side effects: set success

```c
/* list.h */

/* If 0 <= n < length(p), return the nth element of the list p and set success to 1. Otherwise (if n is out of range) return 0 and set success to 0. */

int List_nth_key(List_T p, int n, int *success);
```
A good module:

• Encapsulates data
• Manages resources
• Is consistent
• Has a minimal interface
• Detects and handles/reports errors
• Establishes contracts

• **Has strong cohesion**
• Has weak coupling
Strong Cohesion

A well-designed module has **strong cohesion**
- A module's functions should be strongly related to each other

Why?
- Strong cohesion facilitates abstraction
### Strong Cohesion Examples

<table>
<thead>
<tr>
<th>Library</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>List</strong></td>
<td>(+) All functions are related to the encapsulated data</td>
</tr>
</tbody>
</table>
| **string.h** | (+) Most functions are related to string handling  
(-) Some functions are not related to string handling: memcpy, memcmp...  
(+ But those functions are similar to string-handling functions |
| **stdio.h** | (+) Most functions are related to I/O  
(-) Some functions don’t do I/O: sprintf, sscanf  
(+ But those functions are similar to I/O functions |
| **SymTable** | (+) All functions are related to the encapsulated data |
Agenda

A good module:

- Encapsulates data
- Manages resources
- Is consistent
- Has a minimal interface
- Detects and handles/reports errors
- Establishes contracts
- Has strong cohesion

- Has weak coupling
Weak Coupling

A well-designed module has **weak coupling**
- Module should be weakly connected to other modules in program
- Interaction **within** modules should be more intense than **among** modules

**Why? Theoretical observations**
- Maintenance: Weak coupling makes program easier to modify
- Reuse: Weak coupling facilitates reuse of modules

**Why? Empirical evidence**
- Empirically, modules that are weakly coupled have fewer bugs

Examples (different from previous)…
Weak Design-time Coupling Example

- Simulator module calls many functions in Airplane
- Strong design-time coupling

- Simulator module calls few functions in Airplane
- Weak design-time coupling
Maintenance-time Weak Coupling Example

- Maintenance programmer changes Client and MyModule together frequently
- Strong maintenance-time coupling

- Maintenance programmer changes Client and MyModule together infrequently
- Weak maintenance-time coupling

Client
- f1()
- f2()

MyModule
- f3()

Changed together often

Client
- f1()

MyModule
- f2()
- f3()
Achieving weak coupling could involve refactoring code:

- Move code from client to module (shown)
- Move code from module to client (not shown)
- Move code from client and module to a new module (not shown)
See also

Connascence, an OO-inspired further expansion on the idea of encapsulation and design structure:

https://dzone.com/articles/about-connascence
Summary

A good module:

• Encapsulates data
• Manages resources
• Is consistent
• Has a minimal interface
• Detects and handles/reports errors
• Establishes contracts
• Has strong cohesion
• Has weak coupling