COS 217: Introduction to Programming Systems

Modules and Interfaces

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

PRINCETON UNIVERSITY

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

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

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

Barbara Liskov, a pioneer in CS

"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."

Barbara Liskov and Stephen Zilles. "Programming with Abstract Data Types." ACM SIGPLAN Conference on Very High Level Languages, April 1974.

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:*

```
struct Node {
  int key;
  struct Node *next;
};

struct List {
  struct Node *first;
};
```

and some *operations:*

```
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*:

```
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

```
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);
```

Nothing stops a client from doing this!

```
p->first = NULL;
```

If you put the representation here, then it's not an **abstract** data type, it's just a data type.

client.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);
}
```

list_linked.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, struct List *q) { ... }

int nth_key(struct List *p, int n) { ... }
```

Encapsulation with ADTs (right!)

list.h

```
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);
```

Including only the declaration in header file **enforces** the abstraction: it keeps clients from accessing fields of the struct, allowing implementation to change

client.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);
}
```

list_linked.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, struct List *q) { ... }
int nth_key(struct List *p, int n) { ... }
```

Specifications

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?

```
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);
```

Specification:

A List *p* **represents** a sequence of integers *σ.*

Operation new(): returns a list *p* **representing** the empty sequence.

Operation insert(*p, i*): if *p* represents *σ,* causes *p* to now represent $i \cdot \sigma$.

Operation concat(*p, q*): if *p* represents σ_1 and *q* represents σ_2, causes *p* to represent $\sigma_1 \cdot \sigma_2$ and leaves *q* representing σ_2.

Operation nth_key(*p, n*): if *p* represents $\sigma_1 \cdot i \cdot \sigma_2$ where the length of σ_1 is *n,* returns *i* otherwise (if the length of the string represented by *p* is $\leq n$), it returns an arbitrary integer.

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.

```
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);
```

```
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);
}
```

```
p:[]
p:[]       q:[]
p:[6]      q:[]
p:[7,6]    q:[]
p:[7,6]    q:[5]
p:[7,6,5]  q:[5]
p:[7,6,5]  q:[5,7,6,5]
return 7
```

Object-Oriented Thinking

C is not inherently an object-oriented language, but can use language features to encourage object-oriented thinking

```
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

- 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

Concrete Question: Abstract Data Type?

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

A. Yes – clients can't know the implementation of `strcpy`, etc.

B. Yes – clients can't know the representation of strings.

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

D. No – clients can know the representation of strings.

E. No – strings are not a datatype.

D

We know the underlying representation of strings.

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:

Function pointer parameter

Call via function pointer

Take address of a function

```
/* 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);
}
```

Agenda

A good module:

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Resource Management

A well-designed module manages resources consistently

- A module should release a resource *iff* the module has claimed that resource
- Examples
  - Object allocates memory $\leftrightarrow$ object frees memory
  - Object opens file $\leftrightarrow$ object closes file

Why?

- Claiming and releasing resources at different levels is error-prone
  - Forget to free memory $\Rightarrow$ memory leak
  - Forget to allocate memory $\Rightarrow$ dangling pointer, seg fault
  - Forget to close file $\Rightarrow$ inefficient use of a limited resource
  - Forget to open file $\Rightarrow$ dangling pointer, seg fault

Resources in Assignment 3

Who allocates and frees the key strings in symbol table?

Potential 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)

Resources in Assignment 3

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 / Diversions from expected resource ownership should be noted explicitly in function comments

```
/* somefile.h */

...

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


…
```

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https://www.usno.navy.mil/USNO/time/master-clock/images/clockvaults.jpg

U.S. Naval Observatory Master Clock

Consistency

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?

```
/* 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 doesn't begin with “List_”

(+) First parameter identifies List_T object

```
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);
```

Oops, let’s fix that!

List (revised)

(+) Each function name begins with “List_”

(+) First parameter identifies List_T object

Agenda

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Minimization

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 ⇒ higher learning costs, higher maintenance costs

SymTable_contains(redundancy)?

Q: Assignment 3's interface has both `SymTable_get()` (which returns NULL if the key is not found) and `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 SymTable_get() can't tell these apart from keys that aren't in the table.

Now hash this one out

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

C

It is only ever used internally, and only in a hash table implementation.

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@hugojehanne

Error Handling

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

Reporting Errors in C

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

- Use **function return value**?

```
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**?

```
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 ☹

Reporting Errors in C

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

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

```
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

Reporting Errors in C

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

- Call `assert` macro?

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

- Asserts could be disabled
- Error terminates the process!

Reporting Errors in C

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

Programmer Errors

(2) **Programmer** errors

- Errors made by a programmer
- Errors that "should never happen"

- Example: pointer parameter should not be `NULL`, but is: this is a "mismatch" between the caller and callee's contract/expectations/behavior.

- For now, use `assert` to detect and handle, as a user can't do anything about it

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

```
List_T List_new() { ... }

void List_insert (List_T p, int key)
{
  struct Node *n;
  n = malloc(sizeof(*n));
  assert(n != NULL);
  n->key=key; n->next=p->first; p->first=n;
}

void List_concat(List_T p, List_T q) { ... }

int List_nth_key(List_T p, int n) { ... }

void List_free(List_T p) { ... }
```

- 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);`

Error Handling in List

```
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);
```

Operation nth_key(*p*,*n*), if *p* represents $\sigma_1 \cdot i \cdot \sigma_2$ where the length of σ_1 is *n*, returns *i* ; **otherwise (if the length of the string represented by *p* is ≤ *n*), returns an arbitrary integer.**

- 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 List_nth_key(*p*,*n*): if *p* represents $\sigma_1 \cdot i \cdot \sigma_2$ where the length of σ_1 is *n*, returns *i* ; **otherwise (if the length of the string represented by *p* is ≤*n*), fails with an assertion failure or abort( ).**

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

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 <u>blame</u> to contract violators!
  - If all *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

```
/* list.h */

/* Return the nth element of the list p,
if it exists.  Otherwise (if n is
negative or >= the length of the list),
abort the program. */

int List_nth_key(List_T p, int n);
```

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

```
/* 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);
```

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**

One more "contractual" consideration

```
/* 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);
```

Ron Minsky '94

Your caller won't break your contract if you make it impossible to do so!

- List lengths are always non-negative, so perhaps n should be unsigned:

```
int List_nth_key(List_T p, size_t n, int *success);
```

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- **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

List

(+) All functions are related to the encapsulated data

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

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- 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

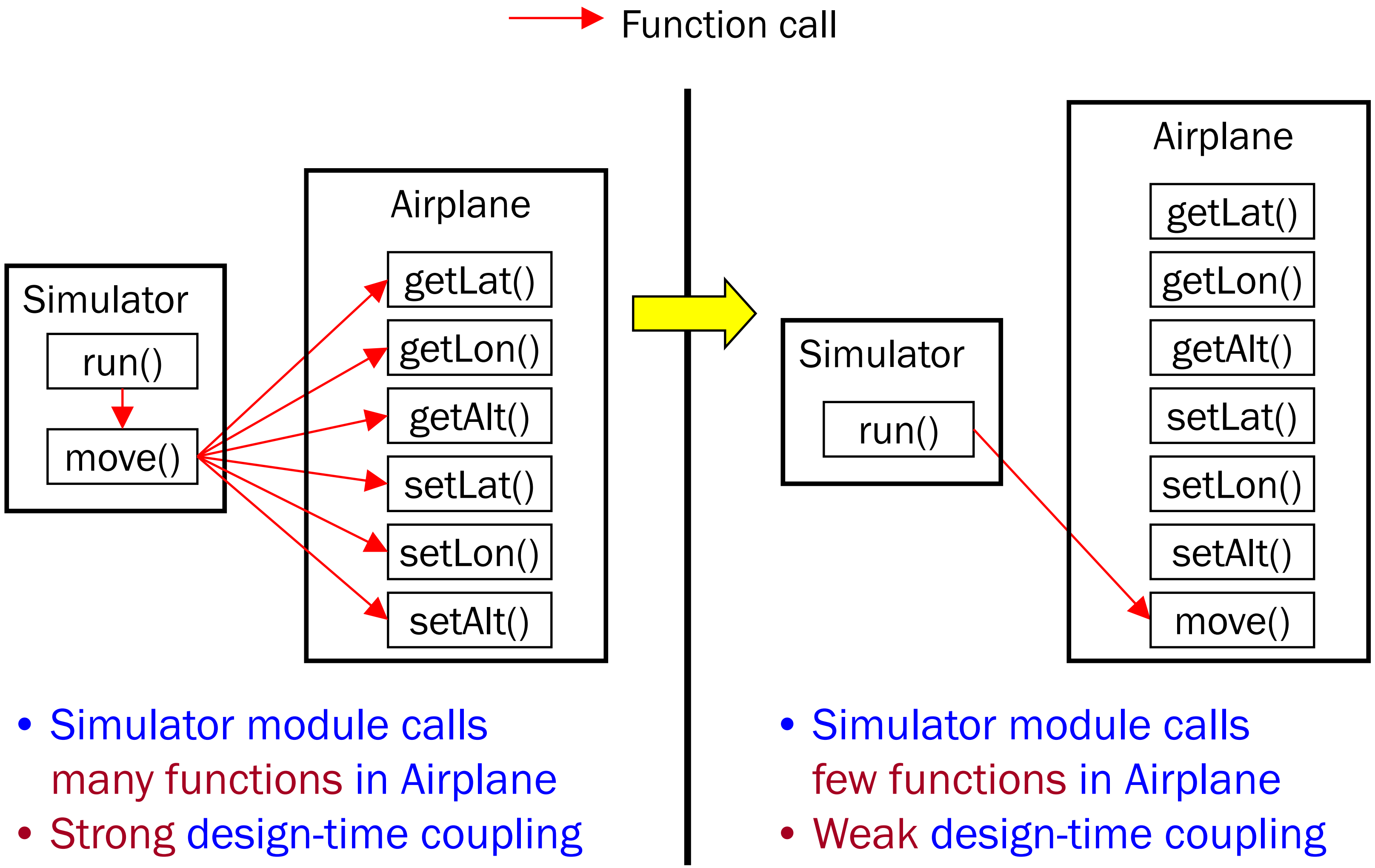
- Maintenance: Weak coupling makes program easier to modify
- Reuse: Weak coupling facilitates reuse of modules

Why? Empirical evidence

- Empirically, modules that are weakly coupled have fewer bugs

Examples (different from previous)…

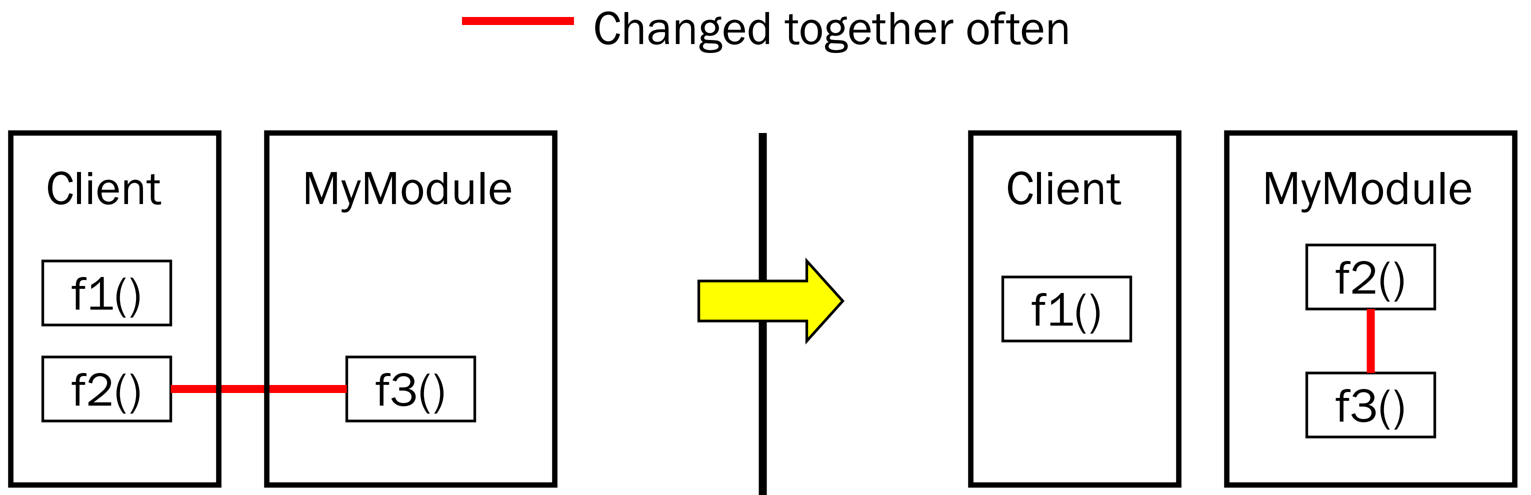
Weak Design-time Coupling Example



- 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

Achieving Weak Coupling

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)

Summary

A good module:

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Sample Exam Questions

S17 Exam2 Q6c: What changes would be needed in a callback function for your A3 symbol table's map function if the implementation of the symbol table is changed from using a linked list to using a hash table?

Sample Exam Question (Spring 2020 Exam 2)

Consider the following program, which consists of 6 files:
{a.h, a.c, b.h, b.c, c.h, c.c}.

a.h:

```
#include <stddef.h>
/* struct a is a thing. you can't see inside, though.
better yet, just think of it as an object */
typedef struct a * a_T;
a_T a_new(const char* src);
size_t aT_to_size_t(a_T a);
void a_free(a_T a);
```

a.c:

```
#include <stdlib.h>
#include <string.h>
#include "a.h"
struct a { size_t a;};
a_T a_new(const char* src) {
 char* res = strstr(src, "a");
 a_T a = malloc(sizeof(*a));
 if(res == NULL) a->a = 0;
 else a->a = res-src;
 return a;
}
size_t aT_to_size_t(a_T a) {
 return a->a;
}
void a_free(a_T a) {
 free(a);
}
```

b.h:

```
/* I need a.h to know what an a_T is. */
#include "a.h"
a_T getAnA(void);
```

b.c:

```
#include "b.h"
#include <stdio.h>enum { LIMIT = 100 };
a_T getAnA(void) {
 char buf[LIMIT];
 scanf("%s", buf);
 return a_new(buf);
}
```

c.h:

```
#include <stdio.h>
#include "b.h"
```

c.c:

```
#include "c.h"
int main(void) {
 a_T at = getAnA();
 printf("%lu\n", aT_to_size_t(at));
 return 0;
}
```

What ambiguity or potential problem is exposed to clients of module A via the return value of the `a_new` function?
Hint – consider the following inputs to the client program :
`ensign`, `lieutenant`, `commander`, `captain`, `admiral`.

Sample Exam Question (Fall 2015, Exam 2)

Consider the **`Queue`** interface:

```
/* A Queue is a first-in-first-out data structure.*/
/* First node of the queue*/
struct QueueNode * first;
/* The last node of the queue*/
struct QueueNode * last;
/* The number of elements in the queue */
int count;
/* Initialize the Queue */
void Queue_init ( void );
/* Free the resources consumed by the Queue */
void Queue_free ( void );
/* Return the number of items in the Queue */
int Queue_getCount ( void );
/* Add item e to the end of the Queue. Return 1 (TRUE) if successful and 0 (FALSE) if memory is exhausted. */
int Queue_enqueue ( void * e );
/* Remove the item at the front of the queue and return it. */
void * Queue_dequeue ( void );
```

Q8b: Briefly describe *two* design problems with this code (i.e., two ways the .h file violates standard practice for modular software development) and how they should be fixed?