

# 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, *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);
```

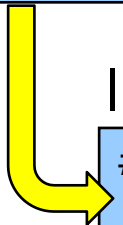
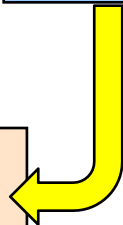
Including only the declaration in header file **enforces** the abstraction: it keeps clients from accessing fields of the struct, allowing implementation to change

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, *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?

## 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.

```
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.

Doctor, it hurts when I do this



Then don't do that!



# Reasoning About Client Code

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

```
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);
}
```

```
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);
```

```
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 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.

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:

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

Function pointer parameter

Call via function pointer

Take address of a function

```
/* 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 \*)

```
/* 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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@frankiefoto





# 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  $\leftrightarrow$  object frees memory
  - Object opens file  $\leftrightarrow$  object closes file

## Why?

- Allocating and freeing 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?

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)



# 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 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 so are responsible
   for freeing it when you no longer
   need it. */
void *f();
...
```

# Agenda



## A good module:

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

U.S. Naval Observatory Master Clock



## 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 begins with "List\_"

(+) First parameter identifies List 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 object

# Agenda



## A good module:

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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  $\Rightarrow$  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.

# Agenda



@hugojeanne

## A good module:

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# 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
- 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

```
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  $\text{nth\_key}(p, n)$ , 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  $\leq n$ ), 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  $\text{nth\_key}(p, n)$ : 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()`.**

# Agenda



## A good module:

- Encapsulates data
- Manages resources
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- 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

```
/* 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  $0 \leq n < \text{length}(p)$ , return the  $n$ th 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  $n$ th element; set **success** appropriately
- Meaning of return value
- Side effects: set **success**

# Agenda



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# 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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- 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

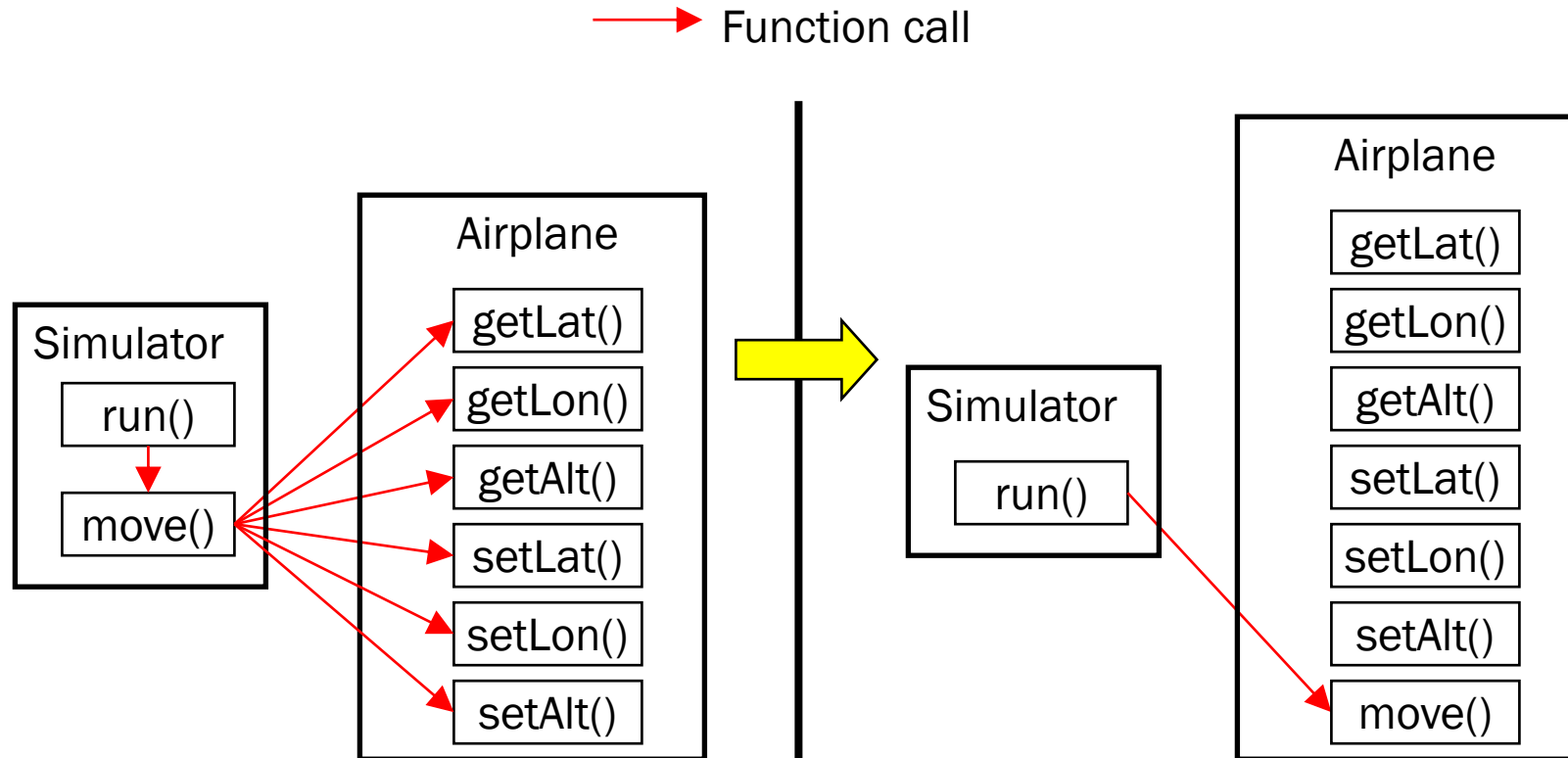
Why? Empirical evidence

- Empirically, modules that are weakly coupled have fewer bugs

Examples (different from previous)...



# Weak Design-time Coupling Example



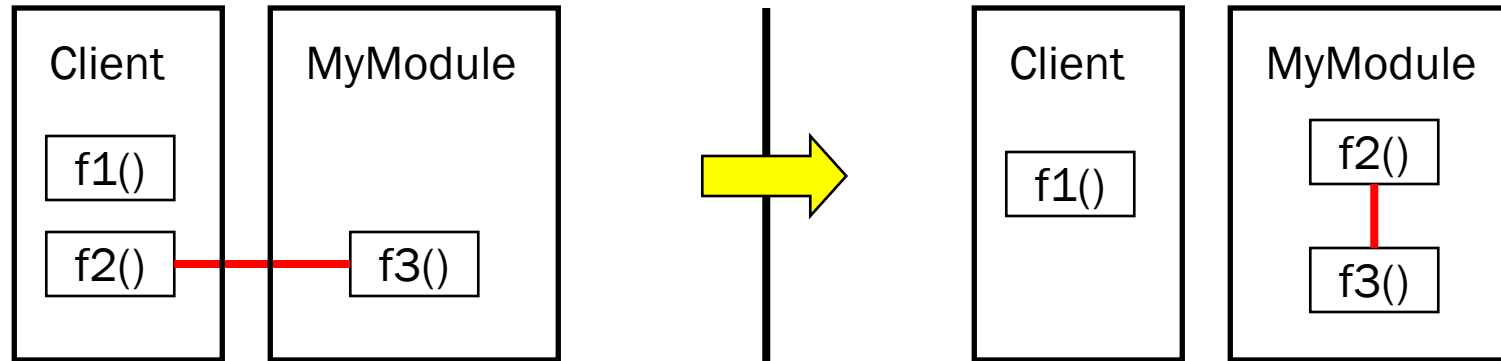
- Simulator module calls many functions in Airplane
- Strong design-time coupling

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



# Maintenance-time Weak Coupling Example

— Changed together often



- 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)



## 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