COS 217 Midterm

When/where?

- In class, Wednesday March 14; split between here and CS 105

What?

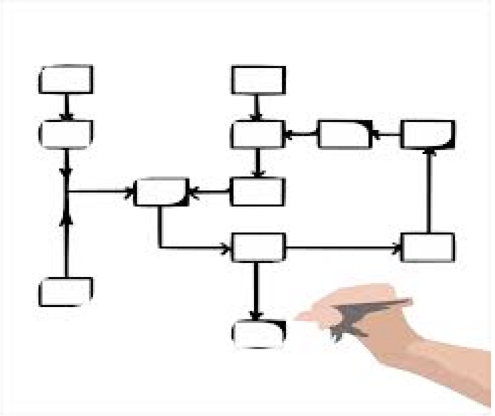
- C programming, including string and stdio
- Numeric representations and types in C
- Programming in the large: modularity, building, testing, debugging
- Readings, lectures, precepts, assignments, through *this week*
- Mixture of short-answer questions and writing snippets of code

How?

- Closed book and notes
- No electronic anything
- Interfaces of relevant functions will be provided

Old exams and study guide will be posted on schedule page

Modules and Interfaces



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 software engineer knows how to find the abstractions in a large program
- A software engineer 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 (if time)
- Has weak coupling (if time)

Encapsulation

A well-designed module encapsulates data

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

Why?

- **Clarity**: Encourages abstraction
- **Security**: Clients cannot corrupt object by changing its data in unintended ways
- **Flexibility**: Allows implementation to change – even the data structure – without affecting clients

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(void) {
  struct List *p;
  p=(struct List *)malloc (sizeof *p);
  assert (p!=NULL);
  p->first = NULL;
  return p;
}

void insert (struct list *p, int key) {
  struct Node *n;
  n = (struct Node *)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);
void insert (struct list *p, int key);
void concat (struct list *p,
             struct list *q);
int nth_key (struct list *p, int n);
```

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.

Encapsulation with ADTs (wrong!)

list.h

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

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);
```

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

(Many C programmers program this way because they don't know any better.)

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(void) {
  struct List *p = (struct List *)malloc(sizeof(*p));
  p->first=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);
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 abstration: 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(void) {
  struct List *p = (struct List *)malloc(sizeof(*p));
  p->first=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?

```
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);
```

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

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);

void insert (List_T p, int key);

void concat (List_T p, List_T q);

int nth_key (List_T p, int n);

void free_list (List_T p);
```

"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 the client

Agenda

A good module:

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- **Manages resources**
- Is consistent
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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

Resource Management in `stdio`

`fopen()` allocates memory for **`FILE`** struct, obtains file descriptor from OS

`fclose()` frees memory associated with **`FILE`** struct, releases file descriptor back to OS

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 last lecture)

Passing Resource Ownership

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

```
somefile.h

…

void *f(void);
/* …
   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. */

…
```

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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`

string

```
/* 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);
…
```

Are function names consistent?

Is parameter order consistent?

Agenda

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- **Has a minimal interface**
- Detects and handles/reports errors
- Establishes contracts
- Has strong cohesion (if time)
- Has weak coupling (if time)

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

iClicker Question

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

iClicker Question

Q: Assignment 3 has **`SymTable_hash()`** defined in implementation, but not 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

Agenda

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- Has a minimal interface
- **Detects and handles/reports errors**
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- Has strong cohesion (if time)
- Has weak coupling (if time)

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)

- 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

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)

- 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 variable

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
  - More info later in the course

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

```
typedef struct List *List_T;

List_T List_new(void);

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);
```

add assert(p) in each of the functions.... try to protect against bad clients

```
void List_insert (List_T p, int key) {
    assert(p);
    . . .
}
```

Error Handling in List

```
typedef struct List *List_T;

List_T List_new(void);

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.**

- This error-handling in List_nth_key is *a bit lame.*
- How to fix it? Some choices:
  - `int List_nth_key (List_T p, int n, int *error);`
  - Or, perhaps better: add an interface function,

int List_length (List_T p); and then,

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*), it 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 (if time)
- Has weak coupling (if time)

Establishing Contracts

A well-designed module establishes contracts

- A module should establish contracts with its clients
- Contracts should describe what each function does, esp:
  - 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 n'th 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 n'th element.
- Meaning of return value
- Side effects
  - (None, by default)

Contracts in List

```
/* list.h */

/* If 0 <= n < 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

A good module:

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

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

A good module:

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

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 interaction **among** modules

Why? Theoretical observations

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

Why? Empirical evidence

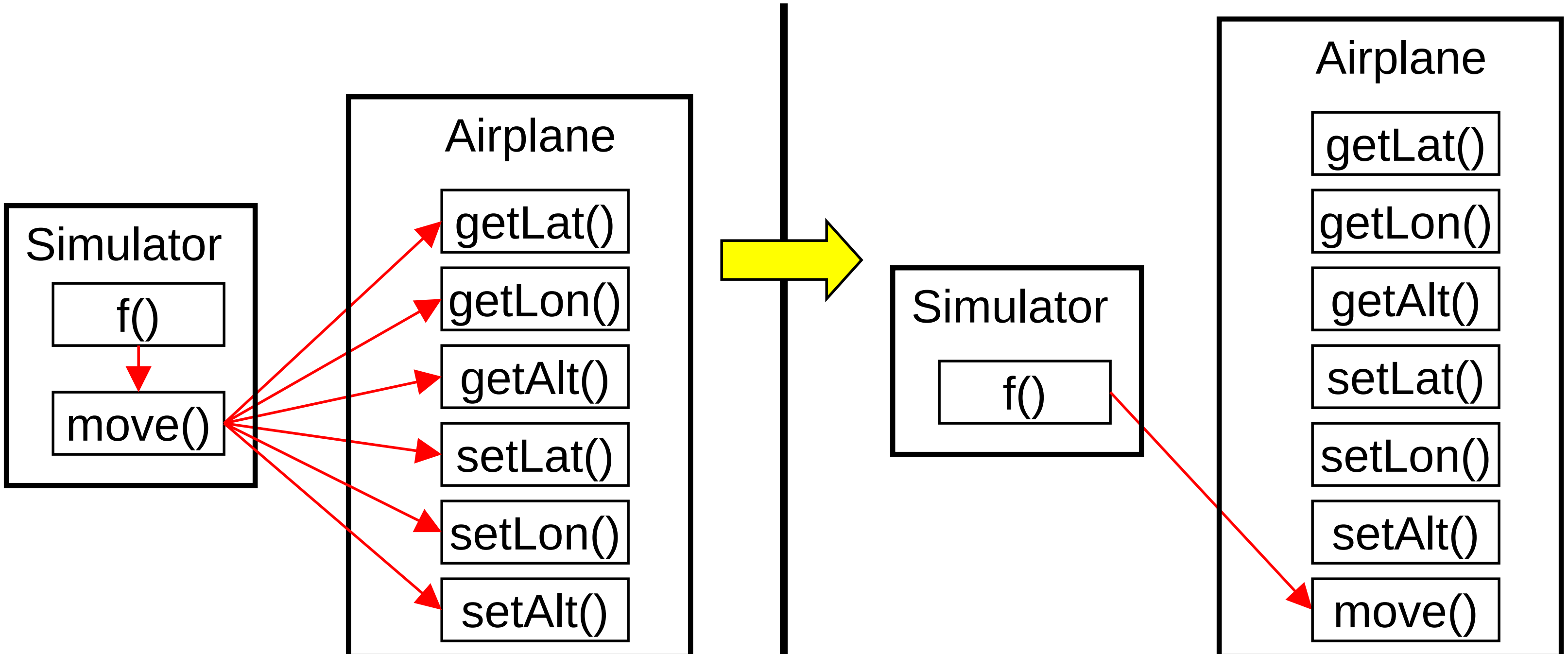
- Empirically, modules that are weakly coupled have fewer bugs

Examples (different from previous)…

Weak Coupling Example 1

Design-time coupling

Function call

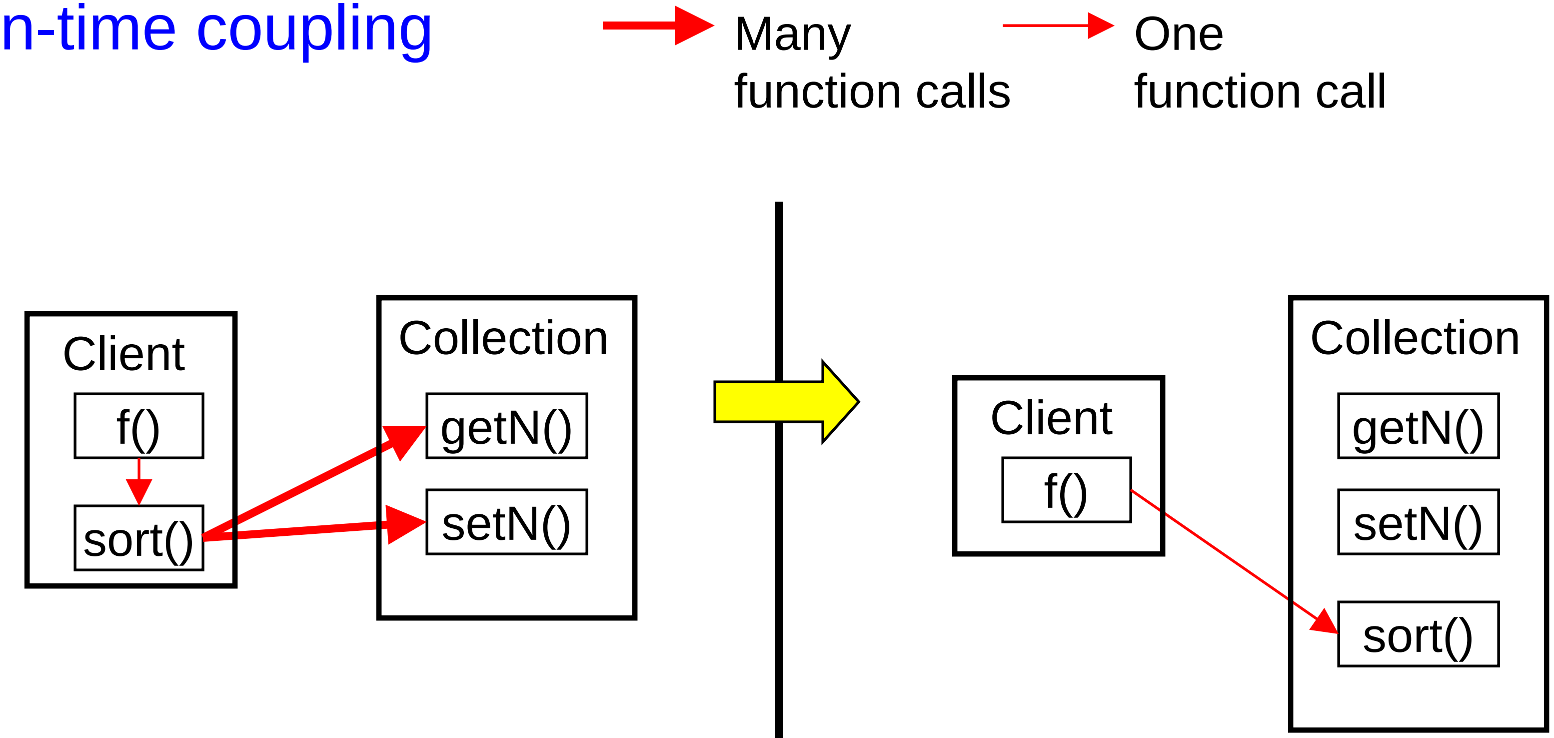


- Simulator module calls many functions in Airplane
- Strong design-time coupling

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

Weak Coupling Example 2

Run-time coupling

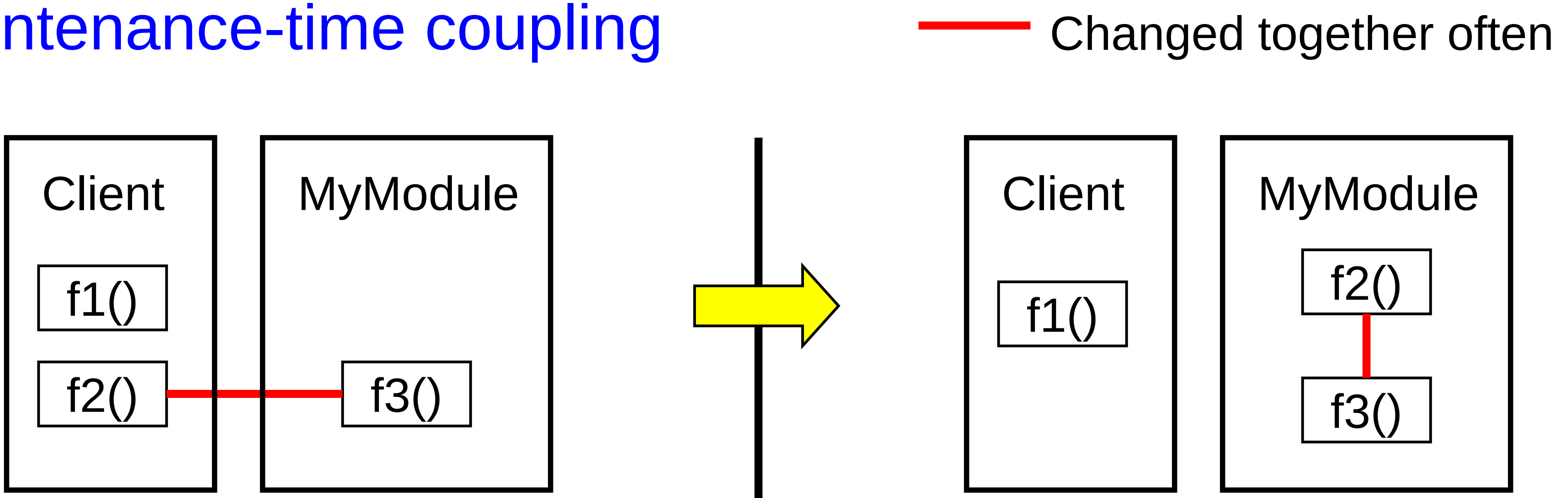


- Client module makes many calls to Collection module
- Strong run-time coupling

- Client module makes few calls to Collection module
- Weak run-time coupling

Weak Coupling Example 3

Maintenance-time coupling



- 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:

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