Modularity

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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 power programmer knows how to find the abstractions in a large program
  - A power programmer knows how to convey a large program's abstractions via its modularity
- Seven module design heuristics...

Interfaces

(1) A well-designed module separates interface and implementation

- Why?
  - Hides implementation details from clients
    - Thus facilitating abstraction
  - Allows separate compilation of each implementation
    - Thus allowing partial builds

Interface Example 1

- Stack: A stack whose items are strings
  - Data structure
    - Linked list
  - Algorithms
    - **new**: Create a new Stack object and return it (or NULL if not enough memory)
    - **free**: Free the given Stack object
    - **push**: Push the given string onto the given Stack object and return 1 (or 0 if not enough memory)
    - **top**: Return the top item of the given Stack object
    - **pop**: Pop a string from the given Stack object and discard it
    - **isEmpty**: Return 1 the given Stack object is empty, 0 otherwise

Interfaces Example 1

- Stack (version 1)

```
/* stack.c */

struct Node {
   const char *item;
   struct Node *next;
};
struct Stack {
   struct Node *first;
};

struct Stack *Stack_new(void) {…}
void  Stack_free(struct Stack *s) {…}
int   Stack_push(struct Stack *s, const char *item) {…}
char *Stack_top(struct Stack *s) {…}
void  Stack_pop(struct Stack *s) {…}
int   Stack_isEmpty(struct Stack *s) {…}
```

```
/* client.c */

#include "stack.c"

/* Use the functions
defined in stack.c. */
```

- Stack module consists of one file (stack.c); no interface
- Problem: Change stack.c => must rebuild stack.c ***and client***
- Problem: Client “sees” Stack function definitions; poor abstraction

Interfaces Example 1

- Stack (version 2)

```
/* stack.h */

struct Node {
   const char *item;
   struct Node *next;
};
struct Stack {
   struct Node *first;
};

struct Stack *Stack_new(void);
void  Stack_free(struct Stack *s);
int   Stack_push(struct Stack *s, const char *item);
char *Stack_top(struct Stack *s);
void  Stack_pop(struct Stack *s);
int   Stack_isEmpty(struct Stack *s);
```

- Stack module consists of two files:

  (1) stack.h (the interface) declares functions and defines data structures

Interfaces Example 1

- Stack (version 2)

```
/* stack.c */

#include "stack.h"

struct Stack *Stack_new(void) {…}
void  Stack_free(struct Stack *s) {…}
int   Stack_push(struct Stack *s, const char *item) {…}
char *Stack_top(struct Stack *s) {…}
void  Stack_pop(struct Stack *s) {…}
int   Stack_isEmpty(struct Stack *s) {…}
```

(2) stack.c (the implementation) defines functions

- #includes stack.h so
  - Compiler can check consistency of function declarations and definitions
  - Functions have access to data structures

Interfaces Example 1

- Stack (version 2)

```
/* client.c */

#include "stack.h"

/* Use the functions declared in stack.h. */
```

- Client #includes only the interface
- Change stack.c => must rebuild stack.c, ***but not the client***
- Client does not “see” Stack function definitions; better abstraction

Interface Example 2

- string (also recall Str from Assignment 2)

```
/* 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 *s, const char *t);
int   strncmp(const char *s, const char *t, size_t n);
char  *strstr(const char *haystack, const char *needle);
…
```

Interface Example 3

- stdio (from C90, vastly simplified)

```
/* stdio.h */

struct FILE {
   int cnt;     /* characters left */
   char *ptr;   /* next character position */
   char *base;  /* location of buffer */
   int flag;    /* mode of file access */
   int fd;      /* file descriptor */
};

#define OPEN_MAX 20
FILE _iob[OPEN_MAX];

#define stdin  (&_iob[0]);
#define stdout (&_iob[1]);
#define stderr (&_iob[2]);
…
```

Don’t be concerned with details

Interface Example 3

- stdio (cont.)

```
…
FILE *fopen(const char *filename, const char *mode);
int   fclose(FILE *f);
int   fflush(FILE *f);

int   fgetc(FILE *f);
int   getc(FILE *f);
int   getchar(void);

int   putc(int c, FILE *f);
int   putchar(int c);

int   fscanf(FILE *f, const char *format, …);
int   scanf(const char *format, …);

int   fprintf(FILE *f, const char *format, …);
int   printf(const char *format, …);
…
```

Encapsulation

(2) 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

Encapsulation Example 1

- Stack (version 1)

```
/* stack.h */

struct Node {
   const char *item;
   struct Node *next;
};
struct Stack {
   struct Node *first;
};

struct Stack *Stack_new(void);
void  Stack_free(struct Stack *s);
void  Stack_push(struct Stack *s, const char *item);
char *Stack_top(struct Stack *s);
void  Stack_pop(struct Stack *s);
int   Stack_isEmpty(struct Stack *s);
```

Structure type definitions in .h file

- That's bad
- Interface reveals how Stack object is implemented (e.g., as a linked list)
- Client can access/change data directly; could corrupt object

Encapsulation Example 1

- Stack (version 2)

```
/* stack.h */

struct Stack;

struct Stack *Stack_new(void);
void  Stack_free(struct Stack *s);
void  Stack_push(struct Stack *s, const char *item);
char *Stack_top(struct Stack *s);
void  Stack_pop(struct Stack *s);
int   Stack_isEmpty(struct Stack *s);
```

Move definition of struct Node to implementation; clients need not know about it

Place ***declaration*** of struct Stack in interface; move ***definition*** to implementation

- That's better
- Interface does not reveal how Stack object is implemented
- Client cannot access data directly

Encapsulation Example 1

- Stack (version 3)

```
/* stack.h */

typedef struct Stack * Stack_T;

Stack_T Stack_new(void);
void  Stack_free(Stack_T s);
void  Stack_push(Stack_T s, const char *item);
char *Stack_top(Stack_T s);
void  Stack_pop(Stack_T s);
int   Stack_isEmpty(Stack_T s);
```

Opaque pointer

- That's better still
- Interface provides "Stack_T" abbreviation for client
- Interface encourages client to view a Stack as an object, not as a (pointer to a) structure
- Client still cannot access data directly; data is "opaque" to the client

Encapsulation Example 2

- string
  - “Stateless” module
  - Has no state to encapsulate!

Encapsulation Example 3

- stdio

```
/* stdio.h */

struct FILE {
   int cnt;     /* characters left */
   char *ptr;   /* next character position */
   char *base;  /* location of buffer */
   int flag;    /* mode of file access */
   int fd;      /* file descriptor */
};
…
```

Structure type definition in .h file

- Violates the heuristic
- Programmers can access data directly
  - Can corrupt the FILE object
  - Can write non-portable code
- But the functions are well documented, so
  - Few programmers examine stdio.h
  - Few programmers are tempted to access the data directly

Resources

(3) 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?
  - Error-prone to allocate and free resources at different levels

What if module allocates memory and nobody frees it?

What if module frees memory that nobody has allocated?

Resources Example 1

- Stack: Who allocates and frees the strings?

  - Reasonable options:

    (1) Client allocates and frees strings
      - **`Stack_push()`** does not create copy of given string
      - **`Stack_pop()`** does not free the popped string
      - **`Stack_free()`** does not free remaining strings

    (2) Stack object allocates and frees strings
      - **`Stack_push()`** creates copy of given string
      - **`Stack_pop()`** frees the popped string
      - **`Stack_free()`** frees all remaining strings

  - Our choice: (1)

Advantages/
disadvantages?

Resources Examples 2, 3

- string
  - Stateless module
  - Has no resources to manage!
- stdio
  - `fopen()` allocates memory, uses file descriptor
  - `fclose()` frees memory, releases file descriptor

SymTable Aside

- Consider SymTable (from Assignment 3)…
- Who allocates and frees the key strings?
  - 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)

Advantages/
disadvantages (recall
last lecture)?

Passing Resource Ownership

- Passing resource ownership
  - Should note violations of the heuristic 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. */

…
```

Consistency

(4) 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 Examples

- Stack
  - (+) Each function name begins with “Stack_”
  - (+) First parameter identifies Stack object
- string
  - (+) Each function name begins with “str”
  - (+) Destination string parameter comes before source string parameter; mimics assignment

Consistency Examples (cont.)

- stdio

```
…
FILE *fopen(const char *filename, const char *mode);
int   fclose(FILE *f);
int   fflush(FILE *f);

int   fgetc(FILE *f);
int   getc(FILE *f);
int   getchar(void);

int   putc(int c, FILE *f);
int   putchar(int c);

int   fscanf(FILE *f, const char *format, …);
int   scanf(const char *format, …);

int   fprintf(FILE *f, const char *format, …);
int   printf(const char *format, …);
…
```

Are function names consistent?

Is parameter order consistent?

Minimization

(5) 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** to make objects complete, or
  - The function is **convenient** for many clients

- Why?
  - More functions => higher learning costs, higher maintenance costs

Minimization Example 1

- Stack

```
/* stack.h */

typedef struct Stack *Stack_T ;

Stack_T Stack_new(void);
void  Stack_free(Stack_T s);
void  Stack_push(Stack_T s, const char *item);
char *Stack_top(Stack_T s);
void  Stack_pop(Stack_T s);
int   Stack_isEmpty(Stack_T s);
```

Should any functions be eliminated?

Minimization Example 1

- Another Stack function?

```
void Stack_clear(Stack_T s);
```

  - Pops all items from the Stack object

Should the Stack ADT define Stack_clear()?

Minimization Example 2

- 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 *s, const char *t);
int    strncmp(const char *s, const char *t, size_t n);
char  *strstr(const char *haystack, const char *needle);
…
```

Should any functions be eliminated?

Minimization Example 3

- stdio

```
…
FILE *fopen(const char *filename, const char *mode);
int    fclose(FILE *f);
int    fflush(FILE *f);

int    fgetc(FILE *f);
int    getc(FILE *f);
int    getchar(void);

int    putc(int c, FILE *f);
int    putchar(int c);

int    fscanf(FILE *f, const char *format, …);
int    scanf(const char *format, …);

int    fprintf(FILE *f, const char *format, …);
int    printf(const char *format, …);
…
```

Should any functions be eliminated?

SymTable Aside

- Consider SymTable (from Assignment 3)
  - Declares `SymTable_get()` in interface
  - Declares `SymTable_contains()` in interface

Should
SymTable_contains()
be eliminated?

SymTable Aside (cont.)

- Consider SymTable (from Assignment 3)
  - Defines `SymTable_hash()` in implementation

Should SymTable_hash() be declared in interface?

- Incidentally: In C any function should be either:
  - **Non-static**, and **declared** in the interface
  - **Static**, and **not declared** in the interface

Error Detection/Handling/Reporting

(6) 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

Detecting and Handling Errors in C

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

- C options for **handling** errors
  - Print 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
  - Set **global variable**?
    - Easy for client to forget to check
    - Bad for multi-threaded programming
  - Use **function return value**?
    - Awkward if return value has some other natural purpose
  - Use extra **call-by-reference parameter**?
    - Awkward for client; must pass additional parameter
  - Call **`assert`** **macro**?
    - Terminates the entire program!
- No option is ideal

In contrast, Java supports "exceptions" (try-catch, throw)

User Errors

Our recommendation: Distinguish between…

(1) **User** errors

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

- Example: Bad 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

Programmer Errors

(2) **Programmer** errors

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

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

- Use **`assert`** to detect and handle

- The distinction sometimes is unclear
  - Example: Write to file fails because disk is full

Error Handling Example 1

- Stack

```
/* stack.c */
…
int Stack_push(Stack_T s, const char *item) {
   struct Node *p;
   assert(s != NULL);
   p = (struct Node*)malloc(sizeof(struct Node));
   if (p == NULL) return 0;
   p->item = item;
   p->next = s->first;
   s->first = p;
   return 1;
}
```

- Invalid parameter is **programmer** error
  - Should never happen
  - Detect and handle via **`assert`**
- Memory allocation failure is **user** error
  - Could happen (huge data set and/or small computer)
  - Detect via **`if`**; report to client via return value

Error Handling Examples 2, 3

- string
  - No error detection or handling/reporting
  - Example: NULL parameter to **`strlen()`** => probable seg fault
- stdlib
  - Detects bad input
  - Uses function return values to report failure
    - Note awkwardness of **`scanf()`**
  - Sets global variable **`errno`** to indicate reason for failure

Establishing Contracts

(7) 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!!!

Establishing Contracts in C

- Our recommendation…
- In C, establish contracts via comments in module interface

Establishing Contracts Example

- Stack

```
/* stack.h */
…
int Stack_push(Stack_T s, const char *item);
/* Push item onto s.  Return 1 (TRUE)
   if successful, or 0 (FALSE) if
   insufficient memory is available. */

…
```

- Comment defines contract:
  - Meaning of function's parameters
    - s is the stack to be affected; item is the item to be pushed
  - Work performed
    - Push item onto s
  - Meaning of return value
    - Indicates success/failure
  - Side effects
    - (None, by default)

Summary: Well-Designed Modules

- (1) Separates interface and implementation
- (2) Encapsulates data
- (3) Manages resources consistently
- (4) Is consistent
- (5) Has a minimal interface
- (6) Detects and handles/reports errors
- (7) Establishes contracts

Appendix

Two additional heuristics

which are more advanced in nature…

Strong Cohesion

(8) 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

- Stack
  - (+) All functions are related to the encapsulated data
- string
  - (+) Most functions are related to string handling
  - (-) Some functions are not related to string handling
    - **`memcpy()`**, **`memmove()`**, **`memcmp()`**, **`memchr()`**, **`memset()`**
  - (+) But those functions are similar to string-handling functions
- stdio
  - (+) 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

Weak Coupling

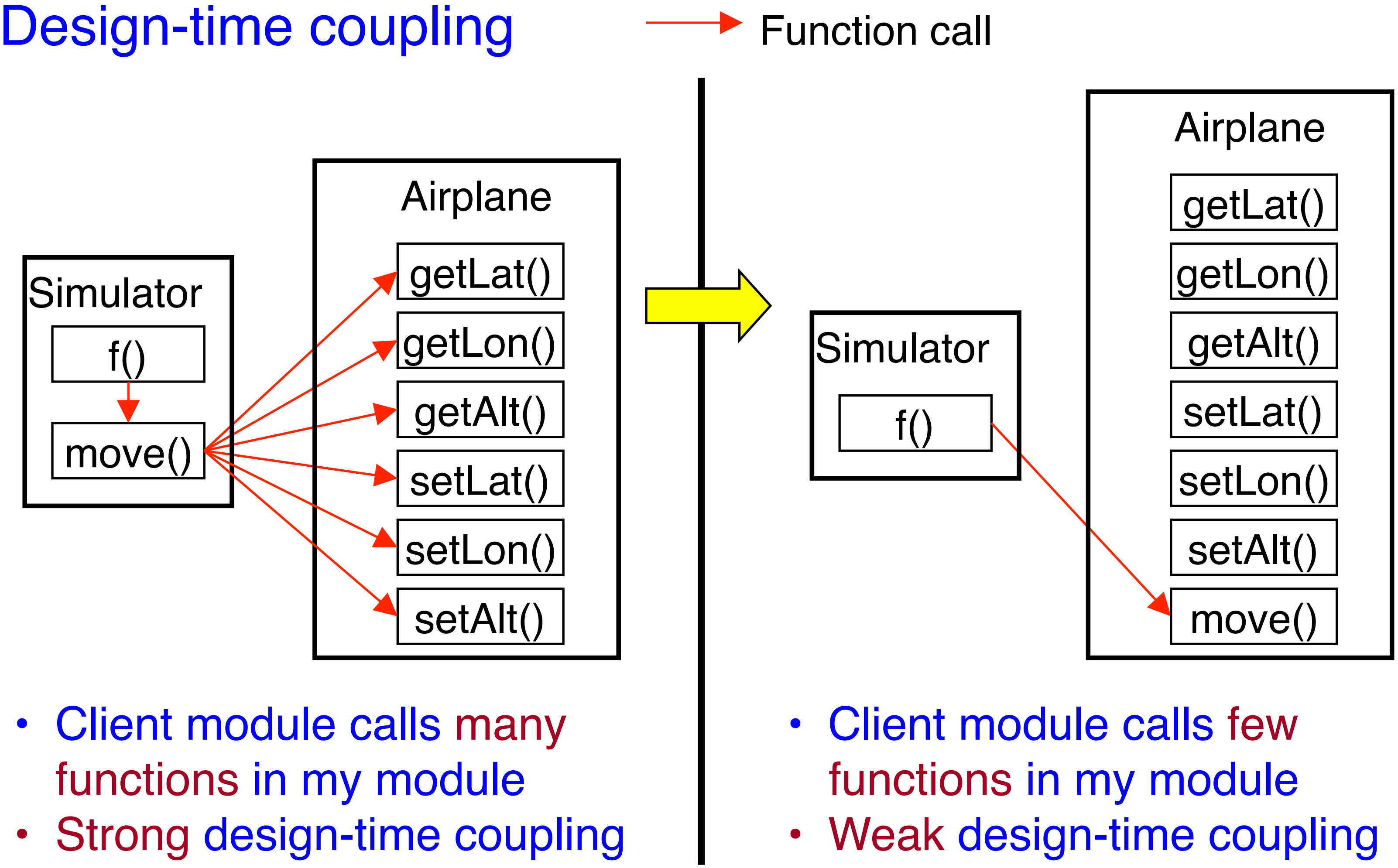
(9) A well-designed module has weak coupling

- 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

Weak Coupling Examples

- Design-time coupling

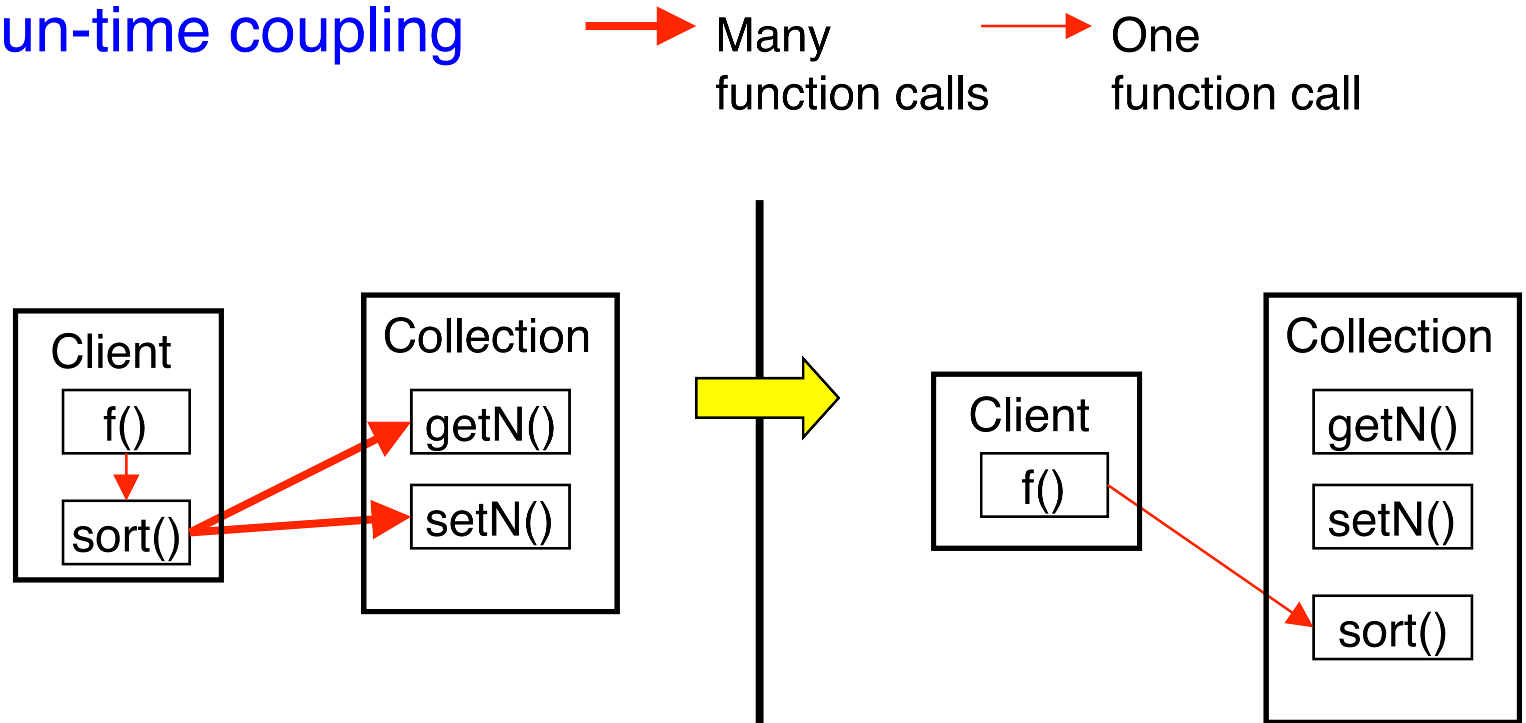


- Client module calls many functions in my module
- Strong design-time coupling

- Client module calls few functions in my module
- Weak design-time coupling

Weak Coupling Examples (cont.)

- Run-time coupling



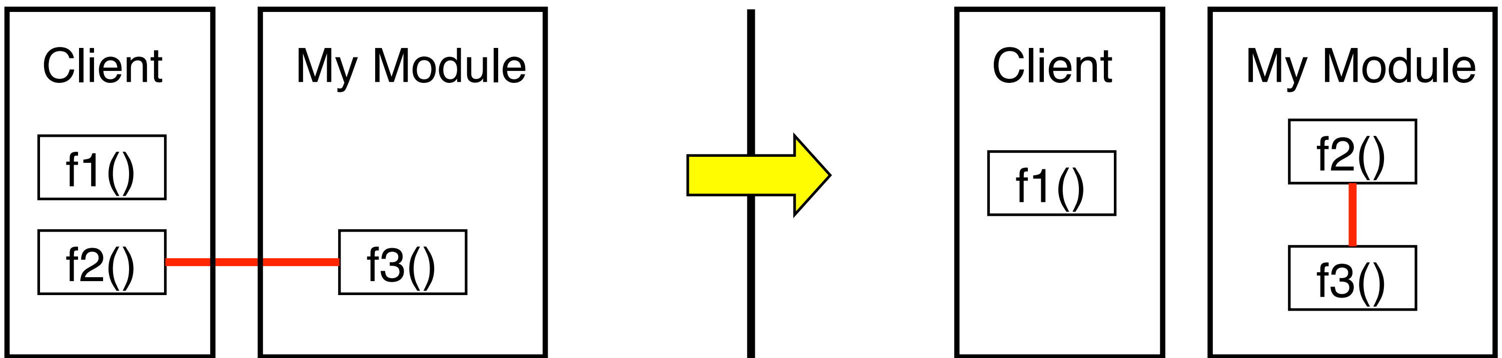
- Client module makes many calls to my module
- Strong run-time coupling

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

Weak Coupling Examples (cont.)

- Maintenance-time coupling

Changed together often



- Maintenance programmer changes client and my module together frequently
- Strong maintenance-time coupling

- Maintenance programmer changes client and my module together infrequently
- Weak maintenance-time coupling

Achieving Weak Coupling

- Achieving weak coupling could involve moving code:
  - From clients to my module (shown)
  - From my module to clients (not shown)
  - From clients and my module to a new module (not shown)

Summary

- A well-designed module:
  - (1) Separates interface and implementation
  - (2) Encapsulates data
  - (3) Manages resources consistently
  - (4) Is consistent
  - (5) Has a minimal interface
  - (6) Detects and handles/reports errors
  - (7) Establishes contracts
  - **(8) Has strong cohesion**
  - **(9) Has weak coupling**