



# Modularity

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

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## 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

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## Module Design Heuristics



- We propose 7 module design heuristics
- Let's consider one at a time...

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## 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

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## 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

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## 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

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# 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

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# 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

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## 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

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## 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);  
char *strcmp(const char *s, const char *t);  
char *strncmp(const char *s, const char *t, size_t n);  
char *strstr(const char *haystack, const char *needle);  
...
```

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## 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

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## 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, ...);  
...
```

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# 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

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# 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

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# 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!

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## 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 */  
};  
...
```

- 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

Structure type  
definition in .h file

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# 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  $\Leftrightarrow$  object frees memory
  - Object opens file  $\Leftrightarrow$  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

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## 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)
  - Recall “key ownership” from last lecture

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## 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. */  
  
...
```

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## 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

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## 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

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## 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?

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## 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

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## 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?

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## 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()?

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## 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);
char *strcmp(const char *s, const char *t);
char *strncmp(const char *s, const char *t, size_t n);
char *strstr(const char *haystack, const char *needle);
...
```

Should any  
functions be  
eliminated?

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## 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?

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## SymTable Aside



- Consider `SymTable` (from Assignment 3)

- Declares `SymTable_get()` in interface
- Declares `SymTable_contains()` in interface

Should `SymTable_contains()` be eliminated?

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## 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

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## 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

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## 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

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## 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

What additional option does Java provide?

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# 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

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# 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

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## 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

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## 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

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## 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!!!

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## Establishing Contracts in C



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

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## 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)

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## 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

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## Appendix



Two additional heuristics  
which are more advanced in nature...

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## 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

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## 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()`, `scanf()`
  - (+) But those functions are similar to I/O functions

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## 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

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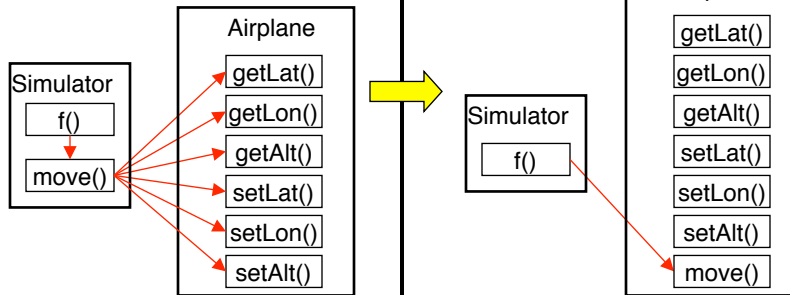


# Weak Coupling Examples



## • Design-time coupling

→ Function call



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

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

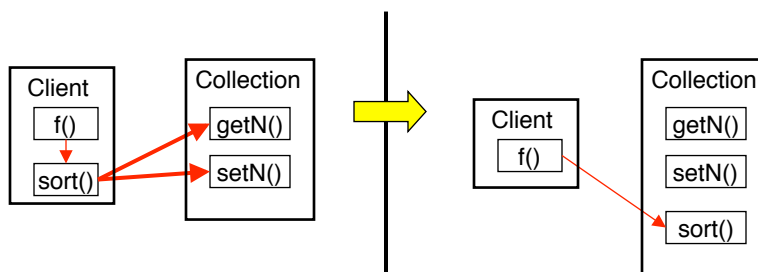
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# Weak Coupling Examples (cont.)



## • Run-time coupling

→ Many function calls      → One function call



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

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

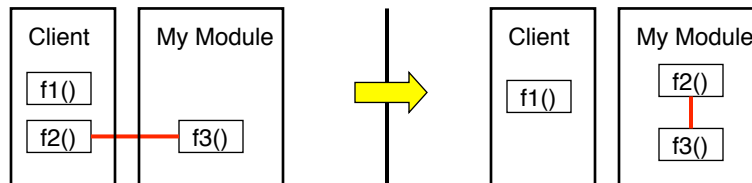
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## Weak Coupling Examples (cont.)



- 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

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## 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)

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# 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**