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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.”
COS 217 Midterm

When/where?
• In class, Thursday October 25; rooms to be announced

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, closed notes
• No electronic anything
• Interfaces of relevant functions will be provided

Old exams and study guide will be posted on schedule page
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
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

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

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

and some operations:

```c
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:

```c
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);
```
"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."

Encapsulation with ADTs (wrong!)

### list.h

```c
#include "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);
```

### list_linked.c

```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) { ... }
```

### client.c

```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 (q,p);
    concat (p,q);
    return nth_key(q,1);
}
```
Encapsulation with ADTs (right!)

**list.h**

```c
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);
```

**client.c**

```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**

```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) { ... }
```
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?

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.

This is OK, but not ideal. Client programs relying on unspecified behavior might break with a new implementation.

```c
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);
```
Reasoning About Client Code

The specifications allow reasoning about the effects of client code.

```c
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);
}
```

```c
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);
```
C is not inherently an object-oriented language, but can use language features to encourage object-oriented thinking.

- 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

```c
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
Q: What’s the weakest assertion you can make that guarantees the following code won’t crash:

```c
int a[1000]; int i, c;
assert ( . . . );
c=getchar(); i=0;
while (isalpha(c))
    { a[i++]=c; c=getchar(); } 
```

A. assert (strlen(a)<1000)
B. assert (sizeof(stdin)<1000)
C. assert (i<1000);
D. assert (1);
E. assert (0);
A good module:

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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 ⇔ object frees memory
  - Object opens file ⇔ object closes file

Why?

- Allocating and freeing resources at different levels is error-prone
  - Forget to free memory ⇒ memory leak
  - Forget to allocate memory ⇒ dangling pointer, seg fault
  - Forget to close file ⇒ inefficient use of a limited resource
  - Forget to open file ⇒ 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
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

```c
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. */

…
```
A good module:
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- **Is consistent**
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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?

Are parameter order consistent?

```c
/* 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);
...```