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Chapter 2

Abstract Data Types

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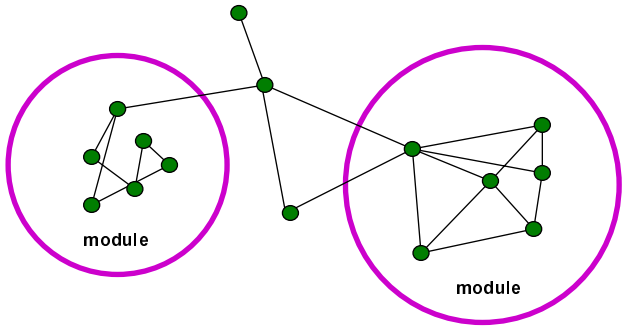
Modularity



● - functions.
\ - function calls.

Program elements that are tightly coupled should be organized as *modules*.
Their connection to the outside world should be minimal.

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Modularity in C

is achieved via Multi-Source Compilation

swap.c

```
void swap(int *x, int *y)
{int t=*x; *x=*y; *y=t; }
```

main.c

```
int main(void)
{ int a=2,b=3;
  swap(&a,&b);
}
```

```
gcc -c swap.c
gcc -c main.c
gcc main.o swap.o -o swap
```

- Code may be divided up between a number of physical source files.
- Each source file `src.c` may be *compiled* separately and independently using

  `gcc -c src.c`

  creating the object file `src.o`.
- Two (or more) object files `src1.o`, `src2.o` may be *linked* to an executable `ex` using

  `gcc src1.o src2.o -o ex`

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Declarations and Definitions in C

swap.h

```
void swap(int*,int*);
```

swap.c

```
#include "swap.h"
void swap(int *x, int *y)
{int t=*x; *x=*y; *y=t; }
```

file1.c

```
#include "swap.h"
int a,b;
swap(&a,&b);  /* OK */
```

file2.c

```
#include "swap.h"
int x = swap(3,4); /*Bang*/
```

- A function *declaration* informs the compiler of the types of the function arguments, and the type of the returned value (prototype). Declarations may appear many times (as long as they are consistent).
- A function *definition* contains the function body (*implementation*). This may appear only once. A definition serves as a declaration.
- All functions should be declared (or defined) before used. If a function is used in a file, but the definition is on a different file, the declaration should be *included* into the file.
- In C, an undeclared function is assumed to return `int`, and its arguments are not checked.

  Never use this "feature" !

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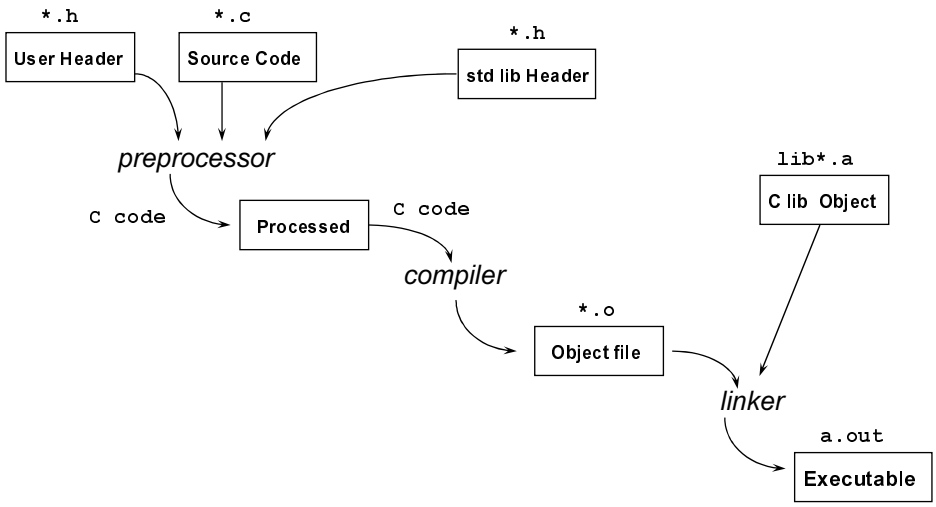
From Source to Executable



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Static Functions

file1.c

```
void do_it(double x, double y)
{ ... }
int a,b;
do_it(a,b); /* calls first do_it() */
```

- **Regular functions are recognized (and may be used) by all C code linked together.**

file2.c

```
static void do_it(double x, double y)
{ ... }
double a,b;
do_it(a,b); /* calls second do_it()*/
```

- **Static functions are recognized *only* in the file in which they are defined.**

file3.c

```
double i,j;
do_it(i,j); /* calls first do_it(),
                    no ambiguities      */
```

- **The linker will not handle two functions with the same name.**

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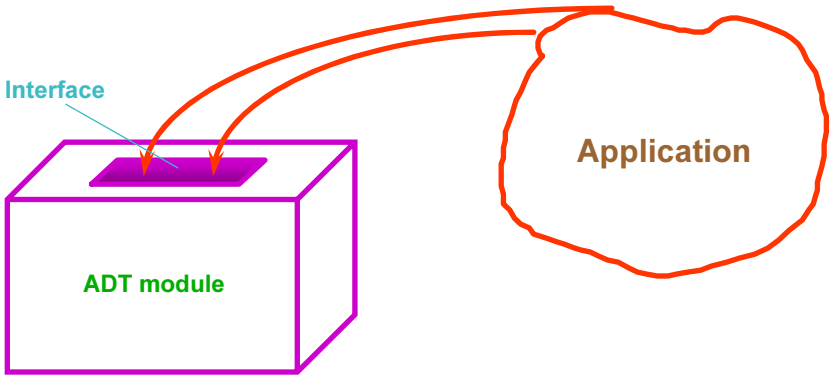
Abstract Data Type



An ADT is a module performing well defined functions with a compact interface.

Example: Complex number.

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Example: Complex Number

Interface

- Create complex number.
- Destroy complex number.
- Get real part.
- Get imaginary part.
- Get absolute value.
- Add/Subtract/Multiply/Divide complex numbers.
- Print complex number.

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Information Hiding

- User of ADT sees only the interface.
- Implementation details are hidden.

Advantages

- Implementation may be changed / improved without user knowing, as long as interface is preserved.
- Provides user with abstract "black box".
- No technical details to confuse user.

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Example: SET of Elements

Interface

- *Create* set of specific elements.
- *Destroy* set.
- *Add* element to set.
- *Remove* element from set.
- *Is* element *in* set ?
- *Is* set *empty* ?
- Enumerate set elements.
- *Union* of two sets.
- *Intersection* of two sets.
- *Print* set.

Other possible interface functions:

Copy set.
Are two sets *equal* ?
Is a set a *subset* of another ?
Size of a set.

Why should (not) these functions be part of the interface ?

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Implementing ADT's in C

- **Separate** header (.h) and body (.c) files.
  - Interface declarations in header.
  - Implementation in body.
- **Separate** Compilation
  - ADT body may be compiled to object (.o) file *without* application.
  - Application may be compiled with *different* implementations.

Example:

ADT files: *set.h set.c*
Application file: set*_app.c*

ADT compilation:
cc -c set.c → *set.o*

Application compilation:
cc set.o set_app.c -o set_app → *set_app*

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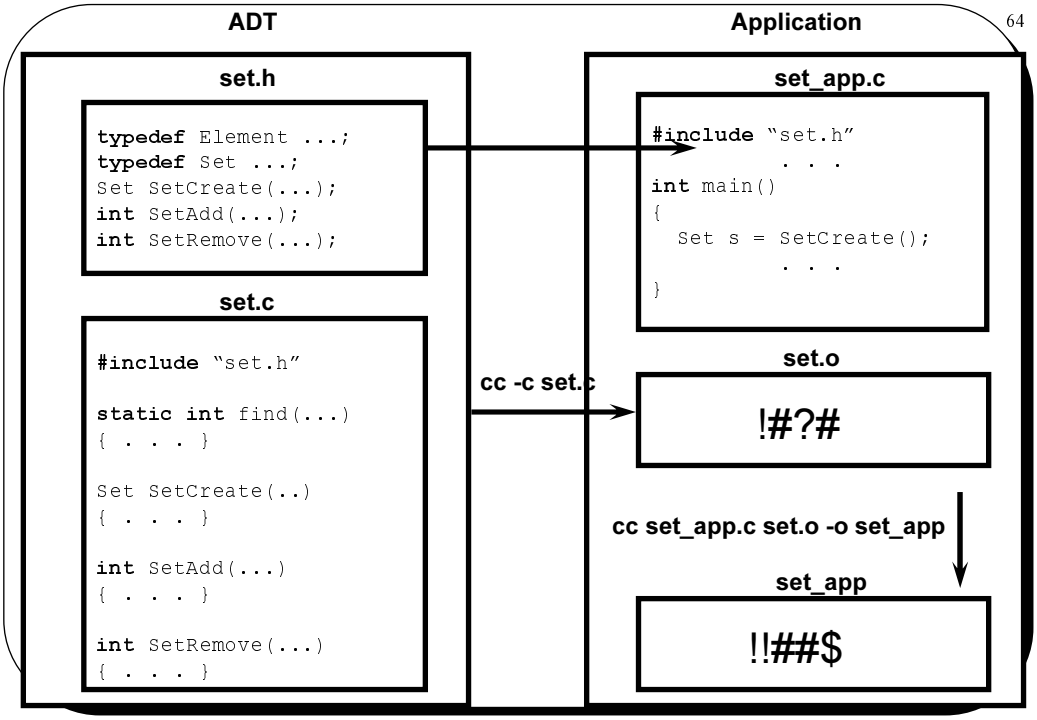

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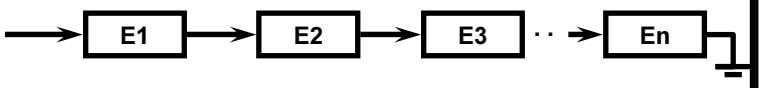
SET - Possible Implementations

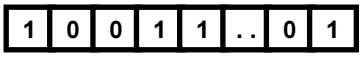
Following are (only) a few of available **container** data-structures, that are capable of storing objects in such ways that allow the behaviour (and an interface) of a set. Even these examples are quite abstract, and each may be implemented in various ways.

- **Array of elements**

- **Linked list**



- **Bit array**



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Array Implementation of SET

- Finite length array of pointers to "elements".
- Empty cells are marked by NULL.
- New element is placed in first empty cell.
- Element is removed by marking cell as empty.
- Element is searched for exhaustively.

Note: The diagram does not reflect the usage of pointers, as stated in the text

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Other SET Implementations Using an Array

- Existing set elements are *moved* to fill in holes.
- Elements are *sorted* in some order (if possible).
- If the array is full, increase its size.

What are the pros and cons of these methods ?

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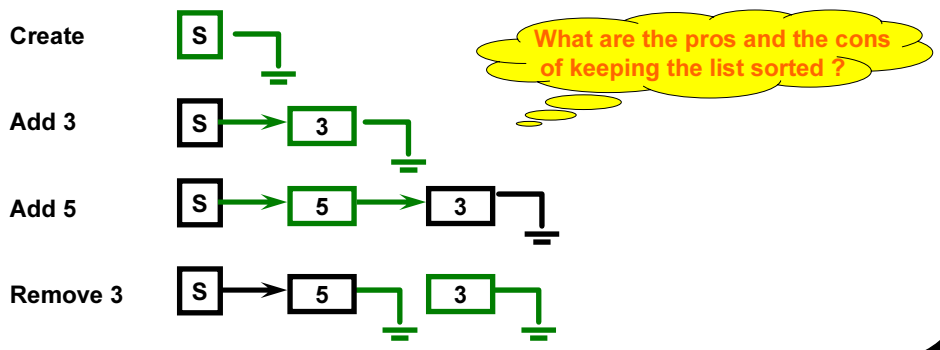
Linked-List Implementation

- Each record represents an element of the set.
- New element is placed at head of list.
- Element is removed by bypassing it.
- Element is searched for exhaustively.



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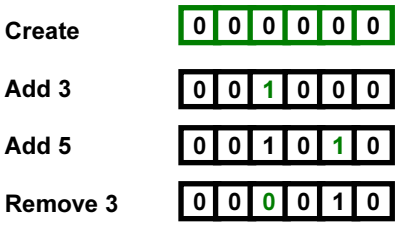
Bit Array Implementation

- Each *possible element* is represented by one bit (present / not present).
- Add / Remove by setting a single bit to 1 or 0.
- Search by checking a single bit.
- Intersection / Union by bitwise operators.
- Set domain must be fixed.



Domain = {1,2,3,4,5,6}

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Implementation Pros and Cons

	Array	Linked List	Bit Array
Set domain size	unlimited	unlimited	limited
Maximal set size	limited	unlimited	limited
Implement	easy	difficult	easy
Search complexity	O(n)	O(n)	O(1)

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SET Contents

Q: What is an element ?

A: An element can be taken from a fixed *domain*.

Examples of domains:

- Set of integers.
- Set of vectors.
- Set of structures.
- Set of sets !!

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SET Implementation in C

- Array of *pointers* to `void`.
- These pointers are cast to the specific element type being used.
- User must supply four functions (the semantics) specific to the element domain on set creation.
  - compare function.
  - copy function.
  - free function.
  - label function (i.e, get a printable value).
- These four functions uniquely characterize the set domain and its intended usage.

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Set Implementation - Coding Style

- In contrast to good practice, in many cases we omit braces (`{, }`) around a single statement at an `if` statement or at a loop statement, e.g,

```
if (..)          instead of      if (..) {
  Do();                              Do();
                                   }
```

(think what happens if `Do()` is a statement MACRO and there is an `else`)

- This is done in order to save lines of code, since space is limited on each slide.
- Note, however, that in the code, that is fully implemented in this chapter, there is not a single function longer than 16 lines (a single slide only).
- Something to think about . . .

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set.h - type definitions

```
#ifndef SET_HDR_  /* '{' */
#define SET_HDR_

typedef enum {FALSE, TRUE} bool; /* C99 has a "faked" type bool
*/

typedef enum {
   SUCCESS = 1,
   FAILURE = -1
} Result;

typedef void* Element;

typedef struct set_rec* Set;
```

Note that the contents of the `set_rec` structure are still unknown.

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set.h - ADT Interface Declarations

```
Set       SetCreate        (bool    cmp(Element,Element),
  /* These parameters */   Element cpy(Element),
  /* are       pointers */  char*   lbl(Element),
  /* to      functions */   void    fre(Element));
void      SetDestroy       (Set);
Result    SetAdd           (Set,Element);
Result    SetRemove        (Set,Element);
bool      SetIsIn          (Set,Element);
int       SetSize          (Set);
int       SetMaxSize       (Set);  /* 0 (or -1) for unlimited */
Set       SetIntersection  (Set,Set);
Set       SetUnion         (Set,Set);
void      SetPrint         (Set);
#define   SetIsEmpty(s)    ((bool)(0 == SetSize(s)))

/* The most primitive iterator - nested loops are forbidden! */
Element   SetNext          (Set);
Element   SetFirst         (Set);
#define SET_FOREACH(e,s) \
            for (e=SetFirst(s);e!=NULL;e=SetNext(s))
#endif /* SET_HDR_ '}' */
```

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set_app.c

```
#include <stdio.h>
#include <stdlib.h>          /* A simple application   */
#include "set.h"             /* using sets of integers. */
#define LABEL_SIZE 20
#define TO_INT(e)   (*(int*)(e))
#define ALLOCATE(var,type)   \
     { if((var =(type *) malloc(sizeof(type))) == NULL)\
       { fprintf(stderr,"Cannot allocate\n"); exit(1);}}


char* int_lbl(Element e)
{   char *s;
    if ((s = malloc(LABEL_SIZE)) == NULL)  return NULL;
    sprintf(s,"%d",TO_INT(e));
    return s;
}
```

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set_app.c

```
bool int_cmp(Element e1,Element e2)
{   return (bool)(TO_INT(e1) == TO_INT(e2));
}


Element int_cpy(Element e)
{   int *j;
    ALLOCATE(j,int);
    *j = TO_INT(e);
    return j;
}
```

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set_app.c

```
int main(void)
{   Set s1 = SetCreate(int_cmp,int_cpy,int_lbl,free),
        s2 = SetCreate(int_cmp,int_cpy,int_lbl,free);
    for (int j = 0; j < 20; j += 2) {  // C99
      SetAdd(s1,&j);
    }
    for (int j = 0; j < 12; j += 3) {
      SetAdd(s2,&j);
    }
    Set s3 = SetUnion(s1,s2),           /* C99 */
        s4 = SetIntersection(s1,s2);
    SetPrint(s1);    SetPrint(s2);
    SetPrint(s3);    SetPrint(s4);
    SetDestroy(s1);  SetDestroy(s2);
    SetDestroy(s3);  SetDestroy(s4);
    return 0;
}
```

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Makefile

ADT

```
set.o: set.h set.c
    gcc -c set.c
```

Client is not interested in (and does not have) set.c

Application

```
set_app: set_app.c set.h set.o
    gcc set_app.c set.o -o set_app
```

output of set_app

```
0 2 4 6 8 10 12 14 16 18
0 3 6 9
0 2 4 6 8 10 12 14 16 18 3 9
0 6
```

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set.c - Implementation as array

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "set.h"
#define MAX_SET_SIZE 1000
struct set_rec {
   Element  elem[MAX_SET_SIZE];
   int      n_elem; /* set size */
   int      last;   /* index of last element */
   int      curr;   /* index of iterator */
   bool     (*lm_cmp) (Element,Element);
   Element  (*lm_cpy) (Element);
   char*    (*lm_lbl) (Element);
   void     (*lm_fre) (Element);
};

#define CREATE_AS(s)  \
  SetCreate((s)->lm_cmp,(s)->lm_cpy,(s)->lm_lbl,(s)->lm_fre)
```

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set.c - Internal functions

```
                    /* find element in set */
static int find(Set s, Element e)
{   for (int j = 0; j < s->last; j++) { // C99
      if (s->elem[j]!=NULL && s->lm_cmp(s->elem[j],e))
         return j;
    }
    return FAILURE;
}

             /* find first empty position in array */
static int find_empty(Set s)
{   int j;
    if (s->n_elem == MAX_SET_SIZE) return FAILURE;
    for (j = 0; j < s->last && s->elem[j] != NULL; j++)
      ;
    return j;  // j  cannot be local in for-loop
}
```

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set.c - Interface Functions

```
Set SetCreate(bool    lm_cmp(Element,Element),
              Element lm_cpy(Element),
              char*   lm_lbl(Element),
              void    lm_fre(Element))
{   Set s = (Set) malloc(sizeof(struct set_rec));
    if (s == NULL)  return NULL;
    s->lm_cmp = lm_cmp;
    s->lm_cpy = lm_cpy;
    s->lm_lbl = lm_lbl;
    s->lm_fre = lm_fre;
    s->n_elem = s->curr = s->last = 0;
    return s;   /* A pointer to a record on the heap   */
}

void SetDestroy(Set s)
{   int i;
    if (s == NULL) return;
    for (i = 0; i < s->last; i++)
      if (s->elem[i] != NULL) s->lm_fre(s->elem[i]);
    free(s);   return;
}
```

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set.c

Note the semantics for SUCCESS

A hidden bug in this function

```
Result SetAdd(Set s, Element e)
{  int empty;
   if (find(s,e) != FAILURE) return SUCCESS;
   if ((empty = find_empty(s)) == FAILURE) return FAILURE;
   s->elem[empty] = s->lm_cpy(e);
   s->n_elem++;
   if (empty == s->last) s->last++;
   return SUCCESS;
}

Result SetRemove(Set s, Element e)
{  int j = find(s,e);
   if (j == FAILURE) return FAILURE;
   s->lm_fre(s->elem[j]);
   s->elem[j] = NULL;
   s->n_elem--;
   return SUCCESS;
}
```

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set.c

```
bool SetIsIn(Set s, Element e)
{ return (bool)(find(s,e) != FAILURE);
}

int SetSize(Set s)
{ return s->n_elem;}

int SetMaxSize(Set s)      /* returns 0 (or -1) if unlimited */
{ return MAX_SET_SIZE;}    /* Cannot be a MACRO */

Element SetNext(Set s)
{ while (s->curr<s->last && s->elem[s->curr] == NULL) s->curr++;
  if (s->curr == s->last) return NULL;
  return s->elem[s->curr++];
}

Element SetFirst(Set s)
{ s->curr = 0;
  return SetNext(s);
}
```

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set.c

```
Set SetIntersection(Set s1, Set s2)
{  int i;
   Set s3 = CREATE_AS(s1);
   if (s3 == NULL)  return NULL;

   for (i = 0; i < s1->last; i++) {/* No SET_FOREACH */
     Element e = s1->elem[i];
     if (e == NULL) continue;
     if (SetIsIn(s2,e)) {
       if (SetAdd(s3,e) == FAILURE) {     /* clean up */
         SetDestroy(s3);
         return NULL;
       }
     }
   }
   return s3;
}
```

Are s1 and s2 sets of the same kind ?

These lines are going to be duplicated.
Look at set.c (addendum)
for an improved implementation

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set.c

```
Set SetUnion(Set s1, Set s2)
{  int i;
   Set s3 = CREATE_AS(s1);
   if (s3 == NULL) return NULL;
   for (i = 0; i < s1->last; i++) {
     Element e = s1->elem[i];
     if (e == NULL) continue;
     if (SetAdd(s3,e) == FAILURE) {
       SetDestroy(s3);
       return NULL;
   } }
   for (i = 0; i < s2->last; i++) {
     Element e = s2->elem[i];
     if ((e == NULL) continue;
     if (SetAdd(s3,e) == FAILURE) {
       SetDestroy(s3);
       return NULL;
   } }
   return s3;
}
```

Are s1 and s2 sets of the same kind ?

Yes, they are duplicated.
Look at set.c (addendum)

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set.c

```
void SetPrint(Set s)
{  Element e;
   int i;

   for (i = 0; i < s->last; i++) { /*DO NOT use SET_FOREACH */
     char *label;
     if ((e = s->elem[i]) == NULL) continue;
     label = s->lm_lbl(e);
     if (label==NULL) {
       printf("ILLEGAL ");
     }else {
       printf("%s ",label);
       free(label);       /* A constraint on s->lm_lbl() */
     }
   }
   printf("\n");
}
```

Look at set.c (addendum) for an improved version

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set.c (addendum)

A helper function

```
static Set addOrDestroy(Set s, Element e)
{ if (SetAdd(s,e) != FAILURE) return s; /* s is never NULL */
  SetDestroy(s);
  return NULL;
}
```

Yes, the set s still exists

```
Set SetIntersection(Set s1, Set s2)
{ int i;
  Set s3 = CREATE_AS(s1);
  if (s3 == NULL)  return NULL;
  for (i = 0; i < s1->last; i++) { /* NO SET_FOREACH */
    Element e = s1->elem[i];
    if (e != NULL && SetIsIn(s2,e))
      if (!addOrDestroy(s3,e)) return NULL;
  }
  return s3;
}
```

Are s1 and s2 sets of the same kind ?

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set.c (addendum)

A helper function

```
static Set addToNew(Set s0, Set s1)
{    /*  C99 */
  for (int i = 0; i < s1->last; i++) { /* NO SET_FOREACH */
    Element e = s1->elem[i];
    if (e != NULL && !addOrDestroy(s0,e)) return NULL;
  }
  return s0;
}
```

Yes, the set `s0` still exists

```
Set SetUnion(Set s1, Set s2)
{ Set s3 = CREATE_AS(s1);
  if (s3 != NULL)
    if (!addToNew(s3,s1) || !addToNew(s3,s2)) return NULL;
  return s3;
}
```

Are s1 and s2 sets of the same kind ?

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set.c (addendum)

```
void SetPrint(Set s) /* Do not use SET_FOREACH */
{ for (int i = 0; i < s->last; i++) { // C99
    Element e = s->elem[i];
    if (e != NULL) {
      char *label = s->lm_lbl(e);
      printf("%s ", label ? label : "ILLEGAL");
      free(label); /*A constraint on s->lm_lbl() */
    }
  }
  printf("\n");
  return;
}
```

`free()` is null-pointer protected

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