Chapter 17

Advanced Uses of Pointers

Dynamic Storage Allocation

- C's data structures, including arrays, are normally fixed in size.
- Fixed-size data structures
  - can be a problem, since we're forced to choose their sizes when writing a program.
- Fortunately, C supports
  - ***dynamic storage allocation:***
  - the ability to allocate storage during program execution.
- Using dynamic storage allocation, we can design data structures that grow (and shrink) as needed.

Dynamic Storage Allocation

- Dynamic storage allocation
  - is used most often for strings, arrays, and structures.
- Dynamically allocated structures
  - can be linked together to form lists, trees, and other data structures.
- Dynamic storage allocation
  - is done by calling a memory allocation (配置) function.

Memory Allocation Functions

- The `<stdlib.h>` header declares three memory allocation functions:

  `malloc`—Allocates a block of memory but doesn't initialize it.
  `calloc`—Allocates a block of memory and clears it.
  `realloc`—Resizes a previously allocated block of memory.

- These functions return a value of type `void *` (a "generic" pointer).

Null Pointers

- If a memory allocation function can't locate a memory block of the requested size,
  - it returns a ***null pointer*.**
- A null pointer is a special value that can be distinguished from all valid pointers.
- After we've stored the function's return value in a pointer variable, we must test to see if it's a null pointer.

Null Pointers

- An example of testing `malloc`'s return value:

```
p = malloc(10000);
if (p == NULL) {
  /* allocation failed; take appropriate action */
}
```

- `NULL` is a macro (defined in various library headers) that represents the null pointer.
- Some programmers combine the call of `malloc` with the `NULL` test:

```
if ((p = malloc(10000)) == NULL) {
  /* allocation failed; take appropriate action */
}
```


Null Pointers

- Pointers test true or false in the same way as numbers.
- All non-null pointers test true;
- only null pointers are false.
- Instead of writing

  `if (p == NULL) …`

  we could write

  `if (!p) …`
- Instead of writing

  `if (p != NULL) …`

  we could write

  `if (p) …`

Dynamically Allocated Strings

- Dynamic storage allocation
  - is often useful for working with strings.
- Strings
  - are stored in character arrays,
  - and it can be hard to anticipate how long these arrays need to be.
- By allocating strings dynamically,
  - we can postpone the decision
  - until the program is running.

Using **malloc** to Allocate Memory for a String

- Prototype for the `malloc` function:

```
void *malloc(size_t size);
```

- `malloc`
  - allocates a block of `size` bytes
  - and returns a pointer to it.

- `size_t` is an unsigned integer type defined in the library.

Using **malloc** to Allocate Memory for a String

- A call of `malloc` that allocates memory for a string of `n` characters:

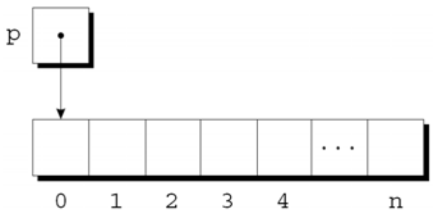
```
p = malloc(n + 1);
```

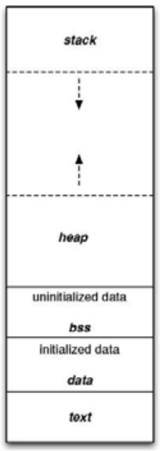
  `p` is a `char *` variable.
- Each character requires one byte of memory; adding 1 to `n` leaves room for the null character.
- Some programmers prefer to cast `malloc`'s return value, although the cast is not required:

```
char *p = (char *) malloc(n + 1);
```


Using **malloc** to Allocate Memory for a String

- Memory allocated using `malloc`
  - isn't cleared,
  - so `p` will point to an uninitialized array of `n` + 1 characters:



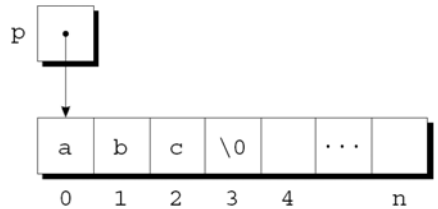


Using **malloc** to Allocate Memory for a String

- Calling `strcpy` is one way to initialize this array:

```
strcpy(p, "abc");
```

- The first four characters in the array will now be `a`, `b`, `c`, and `\0`:



Using Dynamic Storage Allocation in String Functions

- Dynamic storage allocation
  - makes it possible to write functions that return a pointer to a "new" string.
- Consider the problem of writing a function that
  - concatenates two strings without changing either one.
- The function
  - will measure the lengths of the two strings to be concatenated,
  - then call `malloc` to allocate the right amount of space for the result.

Using Dynamic Storage Allocation in String Functions

```
char *concat(const char *s1, const char *s2)
{
  char *result;

  result = malloc(strlen(s1) + strlen(s2) + 1);

  if (result == NULL) {
    printf("Error: malloc failed in concat\n");
    exit(EXIT_FAILURE);
  }

  strcpy(result, s1);
  strcat(result, s2);
  return result;
}
```

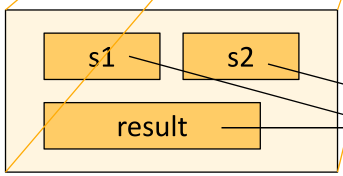

Using Dynamic Storage Allocation in String Functions

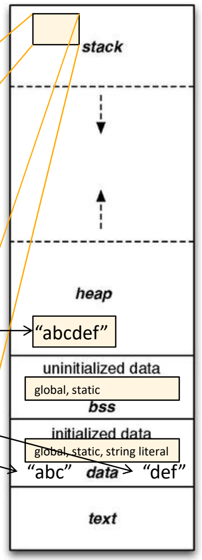
- A call of the `concat` function:

```
p = concat("abc", "def");
```

- After the call, `p` will point to the string `"abcdef"`, which is stored in a dynamically allocated array.

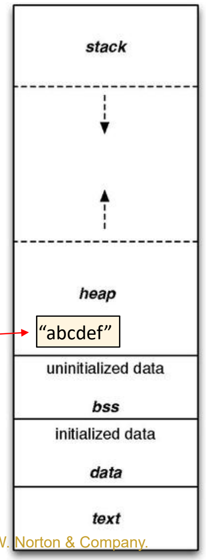
concat function data area





Using Dynamic Storage Allocation in String Functions

- Functions such as `concat`
  - that dynamically allocate storage
  - must be used with care.
- When the string
  - that `concat` returns is no longer needed,
  - we'll want to call the `free` function to release the space that the string occupies.
- If we don't, the program may eventually run out of memory.



Program: Printing a One-Month Reminder List (Revisited)

- The `remind2.c` program
  - is based on the `remind.c` program of Chapter 13,
  - which prints a one-month list of daily reminders.
- The original `remind.c` program
  - stores reminder strings in a two-dimensional array of characters.
- In the new program,
  - the array will be one-dimensional;
  - its elements will be pointers to dynamically allocated strings.

Program: Printing a One-Month Reminder List (Revisited)

- Advantages of switching to dynamically allocated strings:
  - Uses space more efficiently by allocating the exact number of characters needed to store a reminder.
  - Avoids calling `strcpy` to move existing reminder strings in order to make room for a new reminder.
- Switching from a two-dimensional array to an array of pointers requires changing only eight lines of the program (shown in **bold**).

remind2.c

```
/* Prints a one-month reminder list (dynamic string version) */

#include <stdio.h>
#include <stdlib.h>
#include <string.h>

#define MAX_REMIND 50    /* maximum number of reminders */
#define MSG_LEN 60       /* max length of reminder message */

int read_line(char str[], int n);

int main(void)
{
  // char reminders[MAX_REMIND][MSG_LEN+3]; /* remind.c */
  char *reminders[MAX_REMIND];
  char day_str[3], msg_str[MSG_LEN+1];
  int day, i, j, num_remind = 0;
```



```
for (;;) {
  if (num_remind == MAX_REMIND) {
    printf("-- No space left --\n");
    break;
  }

  printf("Enter day and reminder: ");
  scanf("%2d", &day);
  if (day == 0)
    break;
  sprintf(day_str, "%2d", day);
  read_line(msg_str, MSG_LEN);

  // determine where the day belongs
  for (i = 0; i < num_remind; i++)
    if (strcmp(day_str, reminders[i]) < 0)
      break;
  // move all strings below that point down one position
  for (j = num_remind; j > i; j--){
    // strcpy(reminders[j], reminders[j-1]);
    reminders[j] = reminders[j-1];
  }
```

```
24  Susan's birthday
5   6:00 - Dinner with Marge and Russ
26  Movie - "Chinatown"
7   10:30 - Dental appointment
12  Movie - "Dazed 迷惘 and Confused"
5   Saturday class
12  Saturday class
0
```

```
      // 新增
      reminders[i] = malloc(2 + strlen(msg_str) + 1);
      if (reminders[i] == NULL) {
        printf("-- No space left --\n");
        break;
      }

      strcpy(reminders[i], day_str);
      strcat(reminders[i], msg_str);

      num_remind++;
    }

    printf("\nDay Reminder\n");
    for (i = 0; i < num_remind; i++)
      printf(" %s\n", reminders[i]);

    return 0;
  }
```

```
Day Reminder
  5 Saturday class
  5 6:00 - Dinner with Marge and Russ
  7 10:30 - Dental appointment
 12 Saturday class
 12 Movie - "Dazed 迷惘 and Confused"
 24 Susan's birthday
 26 Movie - "Chinatown"
```



```
int read_line(char str[], int n)
{
  int ch, i = 0;

  while ((ch = getchar()) != '\n')
    if (i < n)
      str[i++] = ch;
  str[i] = '\0';

  return i;
}
```


Dynamically Allocated Arrays

- Dynamically allocated arrays have the same advantages as dynamically allocated strings.
- The close relationship between arrays and pointers
  - makes a dynamically allocated array as easy to use as an ordinary array.
- Although `malloc` can allocate space for an array,
  - the `calloc` function is sometimes used instead,
  - since it initializes the memory that it allocates.
- The `realloc` function allows us to make an array "grow" or "shrink" as needed.

Using `malloc` to Allocate Storage for an Array

- Suppose a program needs an array of `n` integers, where `n` is computed during program execution.
- We'll first declare a pointer variable:

```
int *a;
```

- Once the value of `n` is known, the program can call `malloc` to allocate space for the array:

```
a = (int *) malloc(n * sizeof(int));
```

- Always use the `sizeof` operator to calculate the amount of space required for each element.

Using `malloc` to Allocate Storage for an Array

- We can now ignore the fact that `a` is a pointer
  - and use it instead as an array name, thanks to the relationship between arrays and pointers in C.
- For example, we could use the following loop to initialize the array that `a` points to:

```
for (i = 0; i < n; i++)
  a[i] = 0;
```

- We also have the option of using pointer arithmetic instead of subscripting
  - to access the elements of the array.

The `calloc` Function

- The `calloc` function is an alternative to `malloc`.
- Prototype for `calloc`:

```
void *calloc(size_t nmemb, size_t size);
```

- Properties of `calloc`:
  - Allocates space for an array with `nmemb` elements, each of which is `size` bytes long.
  - Returns a null pointer if the requested space isn't available.
  - Initializes allocated memory by setting all bits to 0.

The `calloc` Function

- A call of `calloc` that allocates space for an array of `n` integers:

```
a = calloc(n, sizeof(int));
```

- By calling `calloc` with 1 as its first argument, we can allocate space for a data item of any type:

```
struct point {
   int x, y;
} *p;

p = calloc(1, sizeof(struct point));
```


The `realloc` Function

- The `realloc` function
  - can resize a dynamically allocated array.
- Prototype for `realloc`:

```
void *realloc(void *ptr, size_t size);
```

- `ptr` must point to a memory block obtained by a previous call of `malloc`, `calloc`, or `realloc`.
- `size` represents the new size of the block, which may be larger or smaller than the original size.

The `realloc` Function

- Properties of `realloc`:
  - When it expands a memory block, `realloc` doesn't initialize the bytes that are added to the block.
  - If `realloc` can't enlarge the memory block as requested, it returns a null pointer; the data in the old memory block is unchanged.
  - If `realloc` is called with a null pointer as its first argument, it behaves like `malloc`.

    ```
    realloc(NULL, size_t size);
    ```

  - If `realloc` is called with 0 as its second argument, it frees the memory block.

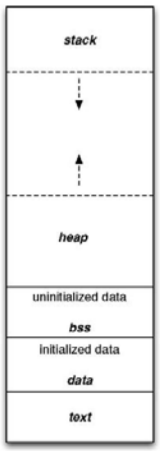
    ```
    realloc(ptr, 0);
    ```


The `realloc` Function

- We expect `realloc` to be reasonably efficient:
  - When asked to reduce the size of a memory block, `realloc` should shrink the block "in place."
  - `realloc` should always attempt to expand a memory block without moving it.
- If it can't enlarge a block,
  - `realloc` will allocate a new block elsewhere,
  - then copy the contents of the old block into the new one.
  - Once `realloc` has returned, be sure to update all pointers to the memory block in case it has been moved.

Deallocating Storage

- `malloc` and the other memory allocation functions obtain memory blocks from a storage pool known as the ***heap***.
- Calling these functions too often
  - —or asking them for large blocks of memory—
  - can exhaust the heap, causing the functions to return a null pointer.
- To make matters worse, a program
  - may allocate blocks of memory and then
  - lose track of them, thereby wasting space.

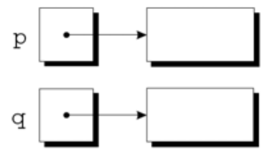


Deallocating Storage

- Example:

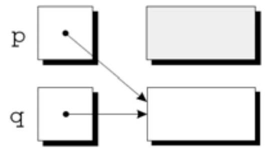
  ```
  p = malloc(…);
  q = malloc(…);
  p = q;
  ```

- A snapshot after the first two statements have been executed:



Deallocating Storage

- After `q` is assigned to `p`, both variables now point to the second memory block:



- There are no pointers to the first block, so we'll never be able to use it again.

Deallocating Storage

- A block of memory that's no longer accessible to a program is said to be ***garbage.***
- A program that leaves garbage behind has a ***memory leak.***
- Some languages provide a ***garbage collector***
  - that automatically locates and recycles garbage,
  - but C doesn't.
- Instead, each C program is responsible for
  - recycling its own garbage
  - by calling the `free` function to release unneeded memory.

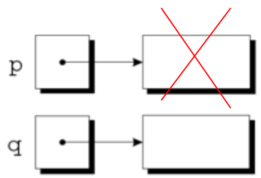
The `free` Function

- Prototype for `free`:

```
void free(void *ptr);
```

- `free` will be passed a pointer to an unneeded memory block:

```
p = malloc(…);
q = malloc(…);
free(p);
p = q;
```

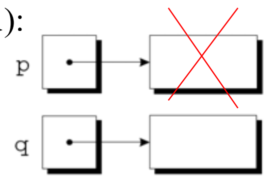


- Calling `free` releases the block of memory that `p` points to.

The "Dangling Pointer" Problem

- Using `free` leads to a new problem: ***dangling pointers.***
- `free(p)` deallocates the memory block that `p` points to, but doesn't change `p` itself.
- If we forget that `p` no longer points to a valid memory block, chaos may ensue (隨之而來):

```
char *p = malloc(4);
…
free(p);
…
strcpy(p, "abc");    /*** WRONG ***/
```



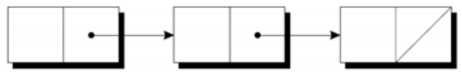
- Modifying the memory that `p` points to is a serious error.

The “Dangling Pointer” Problem

- Dangling （搖擺）pointers
  - can be hard to spot,
  - since several pointers may point to the same block of memory.
- When the block is freed, all the pointers are left dangling.

Linked Lists (鍵結)

- Dynamic storage allocation is especially useful
  - for building lists, trees, graphs, and other linked data structures.
- A ***linked list***
  - consists of a chain of structures (called ***nodes***),
  - with each node containing a pointer to the next node in the chain:



- The last node in the list contains a null pointer.

Linked Lists

- A linked list
  - is more flexible than an array:
  - we can easily insert and delete nodes in a linked list,
  - allowing the list to grow and shrink as needed.
- On the other hand, we lose the “random access” capability of an array:
  - Any element of an array can be accessed in the same amount of time.
  - Accessing a node in a linked list is
    - fast if the node is close to the beginning of the list,
    - slow if it’s near the end.

Declaring a Node Type

- To set up a linked list, we’ll need a structure that represents a single node.
- A node structure will contain data (an integer in this example) plus a pointer to the next node in the list:

```
struct node {
  int value;          /* data stored in the node  */
  struct node *next;  /* pointer to the next node */
};
```

- `node` must be a tag, not a `typedef` name, or there would be no way to declare the type of `next`.

Declaring a Node Type

- Next, we'll need a variable that always points to the first node in the list:

```
struct node *first = NULL;
```

- Setting `first` to `NULL` indicates that the list is initially empty.

Creating a Node

- As we construct a linked list, we'll create nodes one by one, adding each to the list.
- Steps involved in creating a node:
  1. Allocate memory for the node.
  2. Store data in the node.
  3. Insert the node into the list.
- We'll concentrate on the first two steps for now.

Creating a Node

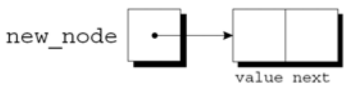
- When we create a node, we'll need a variable that can point to the node temporarily:

```
struct node *new_node;
```

- We'll use `malloc` to allocate memory for the new node, saving the return value in `new_node`:

```
new_node = malloc(sizeof(struct node));
```

- `new_node` now points to a block of memory just large enough to hold a `node` structure:

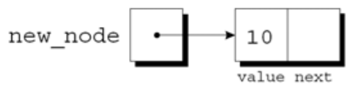


Creating a Node

- Next, we'll store data in the `value` member of the new node:

```
(*new_node).value = 10;
```

- The resulting picture:



- The parentheses around `*new_node`
  - are mandatory
  - because the `.` operator would otherwise take precedence over the `*` operator.

The -> Operator

- Accessing a member of a structure using a pointer is so common that C provides a special operator for this purpose.
- This operator, known as ***right arrow selection,*** is a minus sign followed by `>`.
- Using the `->` operator, we can write

```
new_node->value = 10;
```

instead of

```
(*new_node).value = 10;
```


The -> Operator

- The `->` operator produces an lvalue, so we can use it wherever an ordinary variable would be allowed.
- A `scanf` example:

```
struct node {
    int value;
    struct node *next;
};
```

```
scanf("%d", &new_node->value);
```

- The `&` operator is still required, even though `new_node` is a pointer.

Inserting a Node at the Beginning of a Linked List

- One of the advantages of a linked list is that nodes can be added at any point in the list.
- However, the beginning of a list is the easiest place to insert a node.
- Suppose that
  - `new_node` is pointing to the node to be inserted, and
  - `first` is pointing to the first node in the linked list.

Inserting a Node at the Beginning of a Linked List

- It takes two statements
  - to insert the node into the list.
- The first step
  - is to modify the new node's `next` member to point to the node that was previously at the beginning of the list:

```
new_node->next = first;
```

- The second step
  - is to make `first` point to the new node:

```
first = new_node;
```

- These statements work even if the list is empty.

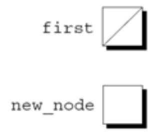
Inserting a Node at the Beginning of a Linked List

- Let's trace the process of inserting two nodes into an empty list.

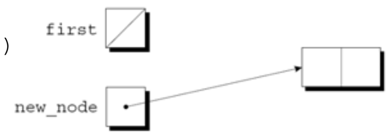
- We'll insert
  - a node containing the number 10 first,
  - followed by a node containing 20.

Inserting a Node at the Beginning of a Linked List

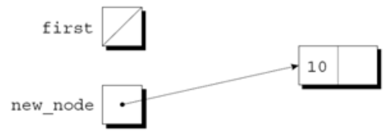
```
first = NULL;
```




```
new_node =
  malloc(sizeof(struct node))
```

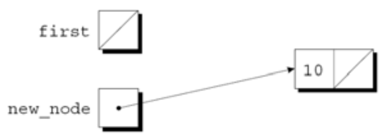



```
new_node->value = 10;
```

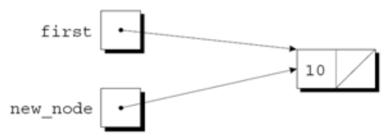


Inserting a Node at the Beginning of a Linked List

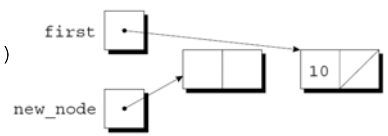
```
//new_node->next = first;
new_node->next = NULL;
```




```
first = new_node;
```

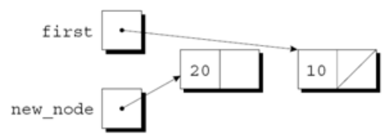



```
new_node =
  malloc(sizeof(struct node))
```

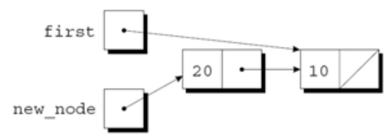


Inserting a Node at the Beginning of a Linked List

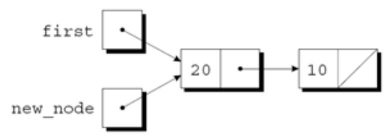
```
new_node->value = 20;
```



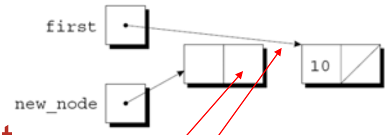

```
new_node->next = first;
```




```
first = new_node;
```



Inserting a Node at the Beginning of a Linked List

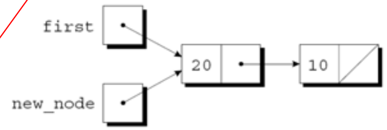


- A function that inserts a node containing n into a linked list, which pointed to by `list`:

```
struct node *add_to_list(struct node *list, int n)
{
  struct node *new_node;

  new_node = malloc(sizeof(struct node));
  if (new_node == NULL) {
    printf("Error: malloc failed in add_to_list\n");
    exit(EXIT_FAILURE);
  }
  new_node->value = n;
  new_node->next = list;

  return new_node;
}
```



Inserting a Node at the Beginning of a Linked List

- Note that `add_to_list`
  - returns a pointer to the newly created node (now at the beginning of the list).
- When we call `add_to_list`, we'll need to store its return value into `first`:

```
first = add_to_list(first, 10);
first = add_to_list(first, 20);
```

- Getting `add_to_list` to update `first` directly, rather than return a new value for `first`, turns out to be tricky.

Inserting a Node at the Beginning of a Linked List

- A function that uses `add_to_list` to create a linked list containing numbers entered by the user:

```
struct node *read_numbers(void)
{
  struct node *first = NULL;
  int n;

  printf("Enter a series of integers (0 to terminate): ");
  for (;;) {
    scanf("%d", &n);
    if (n == 0)
      return first;
    first = add_to_list(first, n);
  }
}
```

- The numbers will be in reverse order within the list.

Searching a Linked List

- Although a `while` loop can be used to search a list, the `for` statement is often superior.
- A loop that visits the nodes in a linked list,
  - using a pointer variable `p`
  - to keep track of the "current" node:

```
for (p = first; p != NULL; p = p->next)
  …
```

- A loop of this form can be used in a function
  - that searches a list for an integer `n`.

Searching a Linked List

- If it finds n, the function will return
  - a pointer to the node containing n;
  - otherwise, it will return a null pointer.
- An initial version of the function:

```
struct node *search_list(struct node *list, int n)
{
  struct node *p;

  for (p = list; p != NULL; p = p->next)
    if (p->value == n)
      return p;

  return NULL;
}
```


Searching a Linked List

- There are many other ways to write search_list.
- One alternative is to eliminate the p variable, instead using list itself to keep track of the current node:

```
struct node *search_list(struct node *list, int n)
{
  for (; list != NULL; list = list->next)
    if (list->value == n)
      return list;
  return NULL;
}
```

- Since list is a copy of the original list pointer, there's no harm in changing it within the function.

Searching a Linked List

- Another alternative:

```
struct node *search_list(struct node *list, int n)
{
  for (; list != NULL && list->value != n;
         list = list->next)
    ;

  return list;
}
```

- Since list is NULL
  - if we reach the end of the list,
  - returning list is correct even if we don't find n.

Searching a Linked List

- This version of search_list might be a bit clearer if we used a while statement:

```
struct node *search_list(struct node *list, int n)
{
  while (list != NULL && list->value != n)
    list = list->next;

  return list;
}
```

Deleting a Node from a Linked List

- A big advantage of storing data in a linked list
  - is that we can easily delete nodes.
- Deleting a node involves three steps:
  1. Locate the node to be deleted.
  2. Alter the previous node so that it "bypasses" the deleted node.
  3. Call `free` to reclaim the space occupied by the deleted node.
- Step 1 is harder than it looks, because step 2 requires changing the *previous* node.
- There are various solutions to this problem.

Deleting a Node from a Linked List

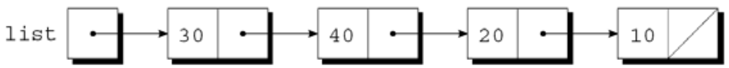
- The "trailing (尾隨) pointer" technique
  - involves keeping a pointer to the previous node (`prev`)
  - as well as a pointer to the current node (`cur`).
- Assume that
  - `list` points to the list to be searched and
  - `n` is the integer to be deleted.
- A loop that implements step 1:

```
for (cur = list, prev = NULL;
     cur != NULL && cur->value != n;
     prev = cur, cur = cur->next)
  ;
```

- When the loop terminates,
  - `cur` points to the node to be deleted and
  - `prev` points to the previous node.

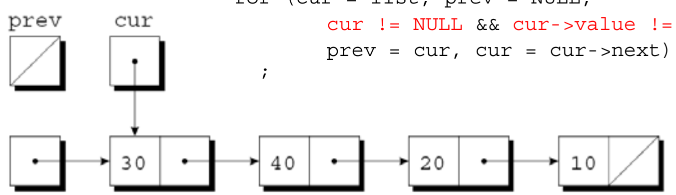
Deleting a Node from a Linked List

- Assume that `list` has the following appearance and `n` is 20:



- After `cur = list, prev = NULL` has been executed:

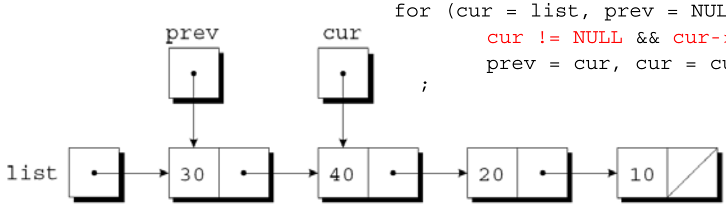
```
for (cur = list, prev = NULL;
     cur != NULL && cur->value != n;
     prev = cur, cur = cur->next)
  ;
```



Deleting a Node from a Linked List

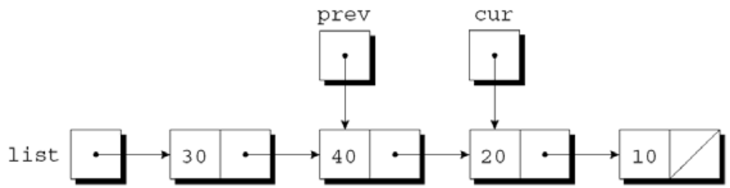
- The test `cur != NULL && cur->value != n` is true, since `cur` is pointing to a node and the node doesn't contain 20.
- After `prev = cur, cur = cur->next` has been executed:

```
for (cur = list, prev = NULL;
     cur != NULL && cur->value != n;
     prev = cur, cur = cur->next)
  ;
```



Deleting a Node from a Linked List

- The test `cur != NULL && cur->value != n` is again true, so `prev = cur, cur = cur->next` is executed once more:



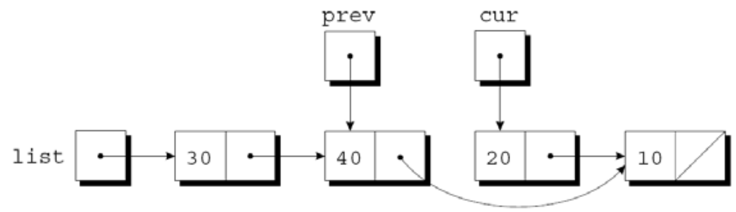
- Since `cur` now points to the node containing 20, the condition `cur->value != n` is false and the loop terminates.

Deleting a Node from a Linked List

- Next, we'll perform the bypass required by step 2.
- The statement

```
prev->next = cur->next;
```

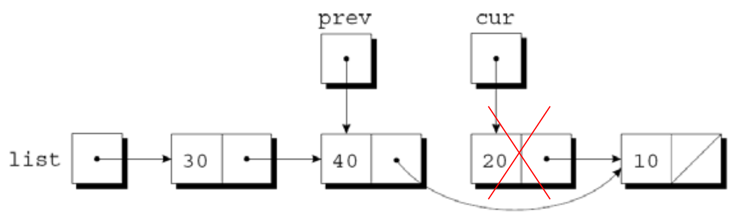
  makes the pointer in the previous node point to the node *after* the current node:



Deleting a Node from a Linked List

- Step 3 is to release the memory occupied by the current node:

```
free(cur);
```



Deleting a Node from a Linked List

- The `delete_from_list` function uses the strategy just outlined.
- When given a list and an integer `n`,
  - the function deletes the first node containing `n`.
- If no node contains `n`,
  - `delete_from_list` does nothing.
- In either case, the function returns
  - a pointer to the list.
- Deleting the first node in the list is a special case that requires a different bypass step.

Deleting a Node from a Linked List

```
struct node *delete_from_list(struct node *list, int n)
{
  struct node *cur, *prev;

  for (cur = list, prev = NULL;
       cur != NULL && cur->value != n;
       prev = cur, cur = cur->next)
    ;
  if (cur == NULL)
    return list;              /* n was not found */

  if (prev == NULL)
    list = list->next;        /* n is in the first node */
  else
    prev->next = cur->next;   /* n is in some other node */

  free(cur);
  return list;
}
```


Ordered Lists

- When the nodes of a list are kept in order
  - —sorted by the data stored inside the nodes—
  - we say that the list is ***ordered.***
- Inserting a node into an ordered list
  - is more difficult,
  - because the node won't always be put at the beginning of the list.
- However, searching is faster:
  - we can stop looking after reaching the point
  - at which the desired node would have been located.

Program: Maintaining a Parts Database (Revisited)

- The `inventory2.c` program
  - is a modification of the parts database program of Chapter 16,
  - with the database stored in a linked list this time.
- Advantages of using a linked list:
  - No need to put a limit on the size of the database.
  - Database can easily be kept sorted by part number.
- In the original program, the database wasn't sorted.

Program: Maintaining a Parts Database (Revisited)

- The `part` structure will contain an additional member (a pointer to the next node):

```
struct part {
  int           number;
  char          name[NAME_LEN+1];
  int           on_hand;
  struct part  *next;
};
```

- `inventory` will point to the first node in the list:

```
struct part *inventory = NULL;
```

Program: Maintaining a Parts Database (Revisited)

- Most of the functions in the new program
  - will closely resemble their counterparts in the original program.
- `find_part` and `insert`
  - will be more complex, however,
  - since we'll keep the nodes in the inventory list sorted by part number.

Program: Maintaining a Parts Database (Revisited)

- In the original program, `find_part`
  - returns an index into the `inventory` array.
- In the new program, `find_part`
  - will return a pointer to the node
  - that contains the desired part number.
- If it doesn't find the part number, `find_part` will return a null pointer.

Program: Maintaining a Parts Database (Revisited)

- Since the list of parts is sorted,
  - `find_part` can stop when it finds a node
  - containing a part number that's greater than or equal to the desired part number.
- `find_part`'s search loop:

```
for (p = inventory;
     p != NULL && number > p->number;
     p = p->next)
  ;
```

- When the loop terminates, we'll need to test whether the part was found:

```
if (p != NULL && number == p->number)
  return p;
```


Program: Maintaining a Parts Database (Revisited)

- The original version of `insert`
  - stores a new part in the next available array element.
- The new version must
  - determine where the new part belongs in the list
  - and insert it there.
- It will also check whether the part number is already present in the list.
- A loop that accomplishes both tasks:

```
for (cur = inventory, prev = NULL;
     cur != NULL && new_node->number > cur->number;
     prev = cur, cur = cur->next)
  ;
```

Program: Maintaining a Parts Database (Revisited)

- Once the loop terminates, `insert` will check
  - whether `cur` isn't `NULL` and
  - whether `new_node->number` equals `cur->number`.
  - If both are true, the part number is already in the list.
  - Otherwise, `insert` will insert a new node between the nodes pointed to by `prev` and `cur`.
- This strategy works
  - even if the new part number is larger than any in the list.
- Like the original program, this version requires the `read_line` function of Chapter 16.

inventory2.c

```
/* Maintains a parts database (linked list version) */

#include <stdio.h>
#include <stdlib.h>
#include "readline.h"
#define NAME_LEN 25

struct part {
  int number;
  char name[NAME_LEN+1];
  int on_hand;
  struct part *next;
};

struct part *inventory = NULL;   /* points to first part */

struct part *find_part(int number);
void insert(void);
void search(void);
void update(void);
void print(void);
```



```
/**********************************************************
 * main: Prompts the user to enter an operation code,     *
 *       then calls a function to perform the requested   *
 *       action. Repeats until the user enters the        *
 *       command 'q'. Prints an error message if the user *
 *       enters an illegal code.                          *
 **********************************************************/
int main(void)
{
  char code;

  for (;;) {
    printf("Enter operation code: ");
    scanf(" %c", &code);

    while (getchar() != '\n')   /* skips to end of line */
      ;
```



```
    switch (code) {
      case 'i': insert();
                break;
      case 's': search();
                break;
      case 'u': update();
                break;
      case 'p': print();
                break;
      case 'q': return 0;
      default:  printf("Illegal code\n");
    }
    printf("\n");
  }
}
```

```
/**********************************************************
 * find_part: Looks up a part number in the inventory     *
 *            list. Returns a pointer to the node         *
 *            containing the part number; if the part     *
 *            number is not found, returns NULL.          *
 **********************************************************/
struct part *find_part(int number)
{
  struct part *p;

  for (p = inventory;
       p != NULL && number > p->number;
       p = p->next)
    ;

  if (p != NULL && number == p->number)
    return p;

  return NULL;
}
```



```
/**********************************************************
 * insert: Prompts the user for information about a new   *
 *         part and then inserts the part into the        *
 *         inventory list; the list remains sorted by     *
 *         part number. Prints an error message and       *
 *         returns prematurely if the part already exists *
 *         or space could not be allocated for the part.  *
 **********************************************************/
void insert(void)
{
  struct part *cur, *prev, *new_node;

  new_node = malloc(sizeof(struct part));
  if (new_node == NULL) {
    printf("Database is full; can't add more parts.\n");
    return;
  }

  printf("Enter part number: ");
  scanf("%d", &new_node->number);
```



```
 for (cur = inventory, prev = NULL;
       cur != NULL && new_node->number > cur->number;
       prev = cur, cur = cur->next)
    ;

  if (cur != NULL && new_node->number == cur->number) {
    printf("Part already exists.\n");
    free(new_node);
    return;
  }

  printf("Enter part name: ");
  read_line(new_node->name, NAME_LEN);
  printf("Enter quantity on hand: ");
  scanf("%d", &new_node->on_hand);

  new_node->next = cur;
  if (prev == NULL)
    inventory = new_node;
  else
    prev->next = new_node;
}
```



```
/**********************************************************
 * search: Prompts the user to enter a part number, then  *
 *         looks up the part in the database. If the part *
 *         exists, prints the name and quantity on hand;  *
 *         if not, prints an error message.               *
 **********************************************************/
void search(void)
{
  int number;
  struct part *p;

  printf("Enter part number: ");
  scanf("%d", &number);
  p = find_part(number);

  if (p != NULL) {
    printf("Part name: %s\n", p->name);
    printf("Quantity on hand: %d\n", p->on_hand);
  } else
    printf("Part not found.\n");
}
```

```
/**********************************************************
 * update: Prompts the user to enter a part number.       *
 *         Prints an error message if the part doesn't    *
 *         exist; otherwise, prompts the user to enter    *
 *         change in quantity on hand and updates the     *
 *         database.                                      *
 **********************************************************/
void update(void)
{
  int number, change;
  struct part *p;

  printf("Enter part number: ");
  scanf("%d", &number);
  p = find_part(number);

  if (p != NULL) {
    printf("Enter change in quantity on hand: ");
    scanf("%d", &change);
    p->on_hand += change;
  } else
    printf("Part not found.\n");
}
```

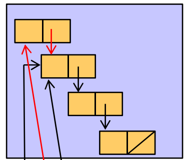


```
/**********************************************************
 * print: Prints a listing of all parts in the database,  *
 *        showing the part number, part name, and         *
 *        quantity on hand. Part numbers will appear in   *
 *        ascending order.                                *
 **********************************************************/
void print(void)
{
  struct part *p;
  printf("Part Number   Part Name                  "
         "Quantity on Hand\n");

  for (p = inventory; p != NULL; p = p->next)
    printf("%7d       %-25s%11d\n", p->number, p->name,
           p->on_hand);
}
```


Pointers to Pointers

- Chapter 13 introduced the idea of a *pointer* to a *pointer*.
- The concept of "pointers to pointers" also pops up frequently in the context of linked data structures.
- In particular, when an argument to a function
  - is a pointer variable,
  - we may want the function to be able to modify the variable.
- Doing so requires the use of a pointer to a pointer.



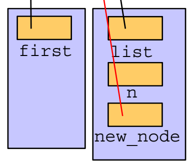
`first = add_to_list(first, 10);`

Pointers to Pointers

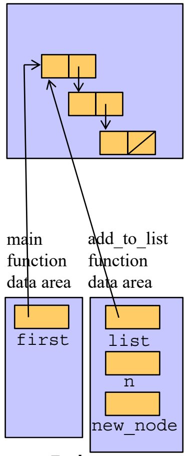
- The `add_to_list` function
  - is passed a pointer to the first node in a list;
  - it returns a pointer to the first node in the updated list:

```
struct node *add_to_list(struct node *list, int n)
{
  struct node *new_node;

  new_node = malloc(sizeof(struct node));
  if (new_node == NULL) {
    printf("Error: malloc failed in add_to_list\n");
    exit(EXIT_FAILURE);
  }
  new_node->value = n;
  new_node->next = list;
  return new_node;
}
```



Pointers to Pointers

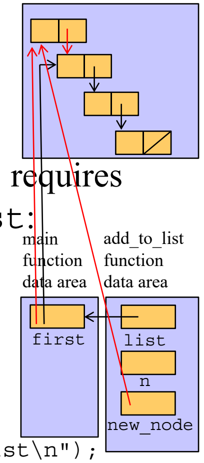


- Modifying `add_to_list`
  – so that it assigns `new_node` to `list`
  – instead of returning `new_node` doesn't work.
- Example:

```
add_to_list(first, 10);
```

- At the point of the call, `first` is copied into `list`.
- If the function
  – changes the value of `list`,
  – making it point to the new node,
  – `first` is not affected.

Pointers to Pointers



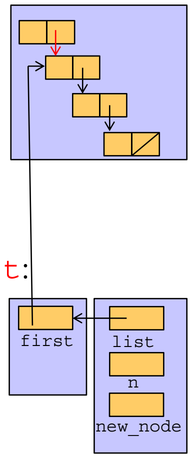
- Getting `add_to_list` to modify `first` requires passing `add_to_list` a *pointer* to `first`:

```
void add_to_list(struct node **list, int n)
{
  struct node *new_node;

  new_node = malloc(sizeof(struct node));
  if (new_node == NULL) {
    printf("Error: malloc failed in add_to_list\n");
    exit(EXIT_FAILURE);
  }

  new_node->value = n;
  new_node->next = *list;
  *list = new_node;
}
```


Pointers to Pointers



- When the new version of `add_to_list` is called,
  – the first argument will be the address of `first`:

```
add_to_list(&first, 10);
```

- Since `list`
  – is assigned the address of `first`,
  – we can use `*list` as an alias for `first`.
- In particular, assigning `new_node` to `*list` will modify `first`.

Pointers to Functions

- C doesn't require that pointers point only to *data*; it's also possible to have pointers to *functions*.
- Functions
  – occupy memory locations,
  – so every function has an address.
- We can use function pointers
  – in much the same way we use pointers to data.
- Passing a function pointer
  – as an argument
  – is fairly common.

Function Pointers as Arguments

- A function named `integrate` that integrates a mathematical function `f` can be made as general as possible by passing `f` as an argument.
- Prototype for `integrate`:

```
double integrate(double (*f)(double),
                 double a, double b);
```

  The parentheses around `*f` indicate that `f` is a pointer to a function.
- An alternative prototype:

```
double integrate(double f(double),
                 double a, double b);
```


Function Pointers as Arguments

- A call of `integrate` that integrates the `sin` (sine) function from 0 to $\pi/2$:

```
result = integrate(sin, 0.0, PI / 2);
```

- When a function name
  - isn't followed by parentheses,
  - the C compiler produces a pointer to the function.
- Within the body of `integrate`, we can call the function that `f` points to:

```
y = (*f)(x);
```

- Writing `f(x)` instead of `(*f)(x)` is allowed.

The `qsort` Function

- Some of the most useful functions in the C library require a function pointer as an argument.
- One of these is `qsort`, which belongs to the `<stdlib.h>` header.
- `qsort`
  - is a general-purpose sorting function
  - that's capable of sorting any array.

The `qsort` Function

- `qsort` must be told how to determine
  - which of two array elements is "smaller."
- This is done by passing `qsort`
  - a pointer to a ***comparison function.***
- When given two pointers `p` and `q` to array elements, the comparison function must return an integer that is:
  - *Negative* if `*p` is "less than" `*q`
  - *Zero* if `*p` is "equal to" `*q`
  - *Positive* if `*p` is "greater than" `*q`

The qsort Function

- Prototype for qsort:

```
void qsort(void *base, size_t nmemb, size_t size,
  int (*compar)(const void *, const void *));
```

- base must point to the first element in the array (or the first element in the portion to be sorted).
- nmemb is the number of elements to be sorted.
- size is the size of each array element, measured in bytes.
- compar is a pointer to the comparison function.

The qsort Function

- When qsort is called,
  - it sorts the array into ascending order,
  - calling the comparison function whenever it needs to compare array elements.
- A call of qsort that sorts the inventory array of Chapter 16:

```
qsort(inventory, num_parts,
      sizeof(struct part), compare_parts);
```

- compare_parts is a function that compares two part structures.

The qsort Function

- Writing the compare_parts function is tricky.
- qsort requires that
  - its parameters have type void *,
  - but we can't access the members of a part structure through a void * pointer.
- To solve the problem,
  - compare_parts will assign its parameters, p and q, to variables of type struct part *.

```
void qsort(void *base, size_t nmemb, size_t size,
  int (*compar)(const void *, const void *));
```


The qsort Function

- A version of compare_parts
  - that can be used to sort the inventory array
  - into ascending order by part number:

```
int compare_parts(const void *p, const void *q)
{
  const struct part *p1 = p;
  const struct part *q1 = q;

  if (p1->number < q1->number)
    return -1;
  else if (p1->number == q1->number)
    return 0;
  else
    return 1;
}
```

The `qsort` Function

- Most C programmers would write the function more concisely:

```
int compare_parts(const void *p, const void *q)
{
  if (((struct part *) p)->number <
      ((struct part *) q)->number)
    return -1;
  else if (((struct part *) p)->number ==
           ((struct part *) q)->number)
    return 0;
  else
    return 1;
}
```


The `qsort` Function

- `compare_parts` can be made even shorter by removing the `if` statements:

```
int compare_parts(const void *p, const void *q)
{
  return ((struct part *) p)->number -
         ((struct part *) q)->number;
}
```


The `qsort` Function

- A version of `compare_parts`
  - that can be used to sort the `inventory` array
  - by part name instead of part number:

```
int compare_parts(const void *p, const void *q)
{
  return strcmp(((struct part *) p)->name,
                ((struct part *) q)->name);
}

struct part {
  int         number;
  char        name[NAME_LEN+1];
  int         on_hand;
  struct part *next;
};
```


Other Uses of Function Pointers

- Although function pointers are often used as arguments, that's not all they're good for.
- C treats pointers to functions just like pointers to data.
- They can be
  - stored in variables or
  - used as elements of an array or
  - as members of a structure or union.
- It's even possible for functions
  - to return function pointers.

Other Uses of Function Pointers

- A variable
  - that can store a pointer to a function with an `int` parameter and a return type of `void`:

```
void (*pf)(int);  /* pf is a variable */
```

- If `f` is such a function,
  - we can make `pf` point to `f` in the following way:

```
pf = f;
```

- We can now call `f` by writing either

```
(*pf)(i);
```

or

```
pf(i);
```


Other Uses of Function Pointers

- An array whose elements are function pointers:

```
void (*file_cmd[])(void) = {new_cmd,
                            open_cmd,
                            close_cmd,
                            close_all_cmd,
                            save_cmd,
                            save_as_cmd,
                            save_all_cmd,
                            print_cmd,
                            exit_cmd
                           };
```


Other Uses of Function Pointers

- A call of the function stored in position `n` of the `file_cmd` array:

```
(*file_cmd[n])();  /* or file_cmd[n](); */
```

- We could get a similar effect with a `switch` statement, but using an array of function pointers provides more flexibility.

Program: Tabulating the Trigonometric Functions

- The `tabulate.c` program prints tables showing the values of the `cos`, `sin`, and `tan` functions.
- The program is built around a function named `tabulate` that,
  - when passed a function pointer `f`,
  - prints a table showing the values of `f`.
- `tabulate` uses the `ceil` function.
- When given an argument `x` of `double` type,
  - `ceil` returns the smallest integer that's greater than or equal to `x`.

Program: Tabulating the Trigonometric Functions

- A session with `tabulate.c`:

```
Enter initial value: 0
Enter final value: .5
Enter increment: .1

     x        cos(x)
  -------    -------
  0.00000    1.00000
  0.10000    0.99500
  0.20000    0.98007
  0.30000    0.95534
  0.40000    0.92106
  0.50000    0.87758
```


Program: Tabulating the Trigonometric Functions

```
     x        sin(x)
  -------    -------
  0.00000    0.00000
  0.10000    0.09983
  0.20000    0.19867
  0.30000    0.29552
  0.40000    0.38942
  0.50000    0.47943

     x        tan(x)
  -------    -------
  0.00000    0.00000
  0.10000    0.10033
  0.20000    0.20271
  0.30000    0.30934
  0.40000    0.42279
  0.50000    0.54630
```


tabulate.c

```
/* Tabulates values of trigonometric functions */

#include <math.h>
#include <stdio.h>

void tabulate(double (*f)(double), double first,
              double last, double incr);

int main(void)
{
  double final, increment, initial;

  printf("Enter initial value: ");
  scanf("%lf", &initial);

  printf("Enter final value: ");
  scanf("%lf", &final);

  printf("Enter increment: ");
  scanf("%lf", &increment);
```



```
  printf("\n      x        cos(x)"
         "\n   -------    -------\n");
  tabulate(cos, initial, final, increment);

  printf("\n      x        sin(x)"
         "\n   -------    -------\n");
  tabulate(sin, initial, final, increment);

  printf("\n      x        tan(x)"
         "\n   -------    -------\n");
  tabulate(tan, initial, final, increment);

  return 0;
}

void tabulate(double (*f)(double), double first,
              double last, double incr)
{
  double x;
  int i, num_intervals;

  num_intervals = ceil((last - first) / incr);
  for (i = 0; i <= num_intervals; i++) {
    x = first + i * incr;
    printf("%10.5f %10.5f\n", x, (*f)(x));
  }
}
```

Restricted Pointers (C99)

- In C99, the keyword `restrict` may appear in the declaration of a pointer:

```
int * restrict p;
```

  `p` is said to be a ***restricted pointer.***
- The intent is that
  - if `p` points to an object that is later modified, then that object is not accessed in any way other than through `p`.
- Having more than one way to access an object
  - is often called ***aliasing.***

Restricted Pointers (C99)

- Consider the following code:

```
int * restrict p;
int * restrict q;
p = malloc(sizeof(int));
```

- Normally it would be legal to copy `p` into `q` and then modify the integer through `q`:

```
q = p;
*q = 0;  /* causes undefined behavior */
```

- Because `p` is a restricted pointer, the effect of executing the statement `*q = 0;` is undefined.

Restricted Pointers (C99)

- To illustrate the use of `restrict`, consider the `memcpy` and `memmove` functions.
- The C99 prototype for `memcpy`,
  - which copies bytes from one object (pointed to by `s2`) to another (pointed to by `s1`):

```
void *memcpy(void * restrict s1,
             const void * restrict s2,
             size_t n);
```

- The use of `restrict` with both `s1` and `s2` indicates that the objects to which they point shouldn't overlap.

Restricted Pointers (C99)

- In contrast, `restrict` doesn't appear in the prototype for `memmove`:

```
void *memmove(void *s1, const void *s2,
              size_t n);
```

- `memmove` is similar to `memcpy`, but is guaranteed to work even if the source and destination overlap.
- Example of using `memmove` to shift the elements of an array:

```
int a[100];
…
memmove(&a[0], &a[1], 99 * sizeof(int));
```

Restricted Pointers (C99)

- Prior to C99, there was no way to document the difference between memcpy and memmove.
- The prototypes for the two functions were nearly identical:

```
void *memcpy(void *s1, const void *s2,
             size_t n);
void *memmove(void *s1, const void *s2,
              size_t n);
```

- The use of restrict in the C99 version of memcpy's prototype is a warning that the s1 and s2 objects should not overlap.

Restricted Pointers (C99)

- restrict provides information to the compiler
  - that may enable it to produce more efficient code
  - —a process known as ***optimization.***
- The C99 standard guarantees that restrict has no effect on the behavior of a program that conforms (遵照) to the standard.
- Most programmers won't use restrict
  - unless they're fine-tuning a program to achieve the best possible performance.

Flexible Array Members (C99)

- Occasionally, we'll need to define a structure that contains an array of an unknown size.
- For example, we might want a structure
  - that stores the characters in a string
  - together with the string's length:

```
struct vstring {
  int len;
  char chars[N];
};
```

- Using a fixed-length array is undesirable: it limits the length of the string and wastes memory.

Flexible Array Members (C99)

- C programmers traditionally solve this problem
  - by declaring the length of chars to be 1
  - and then dynamically allocating each string:

```
struct vstring {
  int len;
  char chars[1];
};
…
struct vstring *str =
  malloc(sizeof(struct vstring) + n - 1);
str->len = n;
```

- This technique is known as the "struct hack."

Flexible Array Members (C99)

- The struct hack is supported by many compilers.
- Some (including GCC) even allow the `chars` array to have zero length.
- The C89 standard
  - doesn't guarantee that the struct hack will work,
  - but a C99 feature known as the ***flexible array member*** serves the same purpose.

Flexible Array Members (C99)

- When the last member of a structure is an array, its length may be omitted:

```
struct vstring {
  int len;
  char chars[]; /* flexible array member - C99 only */
};
```

- The length of the array isn't determined until memory is allocated for a `vstring` structure:

```
struct vstring *str =
  malloc(sizeof(struct vstring) + n);
str->len = n;
```

`sizeof` ignores the `chars` member when computing the size of the structure.

Flexible Array Members (C99)

- Special rules for structures that contain a flexible array member:
  - The flexible array must be the last member.
  - The structure must have at least one other member.
- Copying a structure
  - that contains a flexible array member
  - will copy the other members
  - but not the flexible array itself.

Flexible Array Members (C99)

- A structure that contains a flexible array member is an ***incomplete type.***
- An incomplete type
  - is missing part of the information needed to determine how much memory it requires.
- Incomplete types are subject to various restrictions.
- In particular, an incomplete type can't be a member of another structure or an element of an array.
- However, an array may contain pointers to structures that have a flexible array member.