Systems and Software
Verification Laboratory

MANCHESTER 1824
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Secure C Programming: Memory Management

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Secure C Programming

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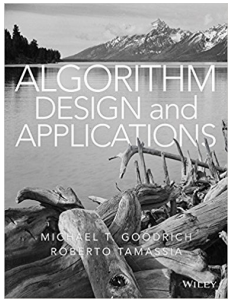
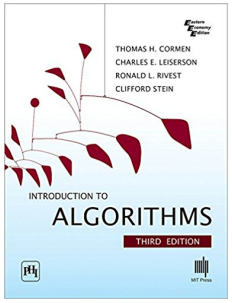
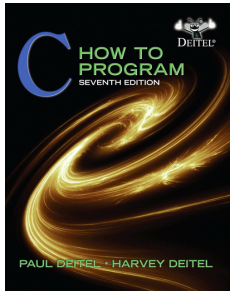
  - Office hours: 15-16 Tuesday, 14-15 Wednesday
- Textbook:
  - *Algorithm Design and Applications* (Chapter 2)
  - *Introduction to Algorithms* (Chapter 10)
  - *C How to Program* (Chapter 12)

These slides are based on the lectures notes of "C How to Program" and "SEI CERT C Coding Standard"







Intended learning outcomes

- Review **dynamic data structures** (linked list)
- Understand **risk assessment** to provide guidance for software developers
- Provide rules for **secure coding** in the C programming language
- Develop **safe**, **reliable**, and **secure** systems
- Eliminating **undefined behaviors** that can lead to undefined program behaviors and **exploitable vulnerabilities**

Risk Assessment

- Each guideline in the CERT C Coding Standard contains a risk assessment section
  - provide software developers with an indication of the **potential consequences** of not addressing a particular rule or recommendation in their code
- This information may be used to **prioritize the repair of rule violations** by a development team
  - The metric is designed primarily for remediation projects
- It is generally assumed that new code will be developed to be compliant with the entire **coding standard** and applicable recommendations

Severity

- How serious are the consequences of the rule being ignored?

Value	Meaning	Examples of Vulnerabilities
1	Low	Denial-of-service attack, abnormal termination
2	Medium	Data integrity violation, unintentional information disclosure
3	High	Run arbitrary code

Likelihood

- How likely is it that a flaw introduced by ignoring the rule can lead to an exploitable vulnerability?

Value	Meaning
1	Unlikely
2	Probable
3	Likelly

Remediation Cost

- How expensive is it to comply with the rule?

Value	Meaning	Detection	Correction
1	High	Manual	Manual
2	Medium	Automatic	Manual
3	Low	Automatic	Automatic

Remediation Cost

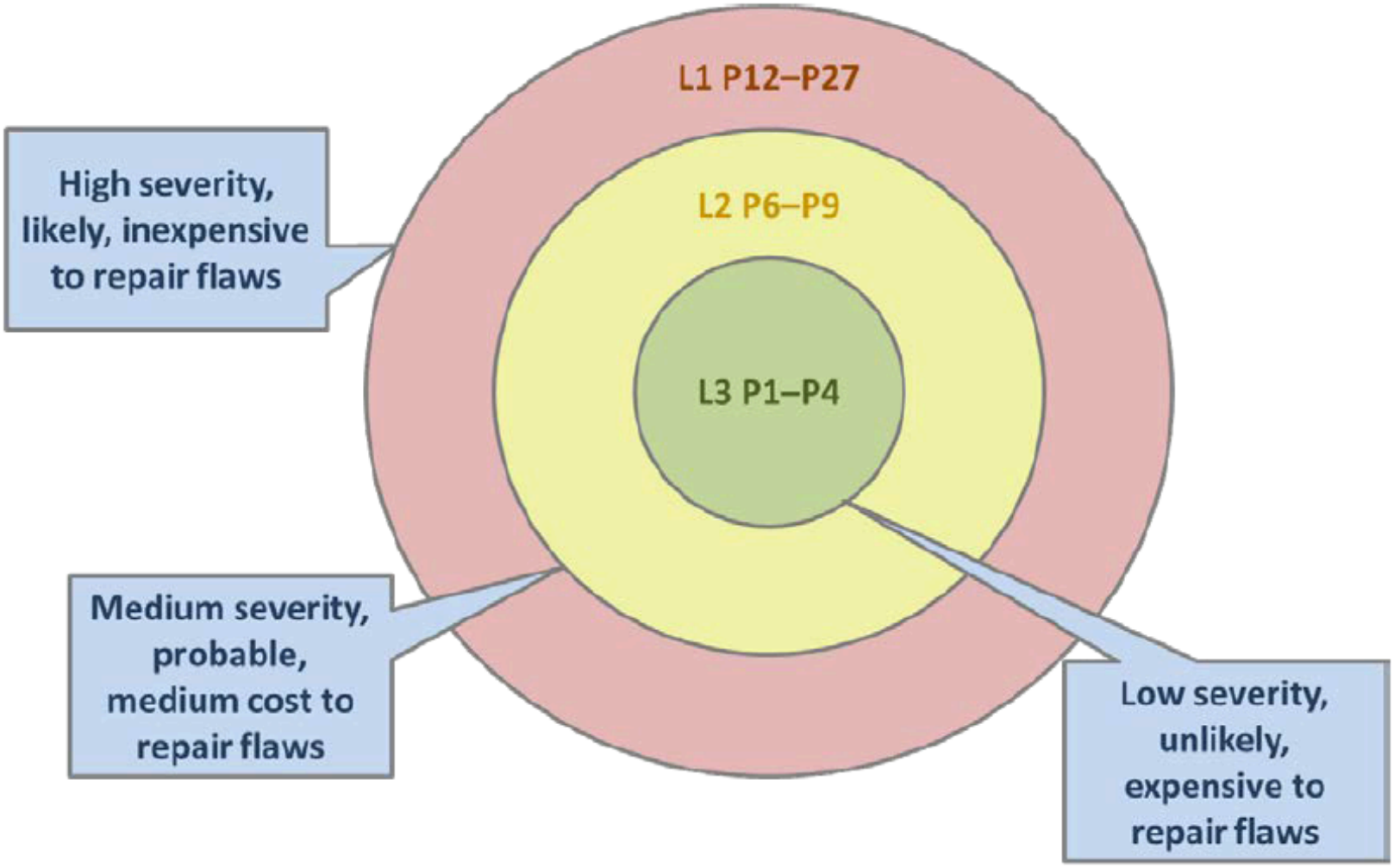
- The **three values are then multiplied** together for each rule
  - This product provides a measure that can be used in prioritizing the application of the rules.
- The products range from **1 to 27**, although only the following **10 distinct values** are possible: **1, 2, 3, 4, 6, 8, 9, 12, 18, and 27**
- Rules and recommendations with a priority in the range of **1 to 4** are **Level 3** rules, **6 to 9** are **Level 2**, and **12 to 27** are **Level 1**

Priorities and Levels

Level	Priorities	Examples of Vulnerabilities
L1	12, 18, 27	High severity, likely, inexpensive to repair
L2	6, 8, 9	Medium severity, probable, medium cost to repair
L3	1, 2, 3, 4	Low severity, unlikely, expensive to repair

Specific projects may begin remediation by implementing all rules at a particular level before proceeding to the lower priority rules

Priorities and Levels



Memory Management (SEI CERT C Coding Standard)

- **MEM30-C:** Do not access freed memory
- **MEM31-C:** Free dynamically allocated memory when no longer needed
- **MEM33-C:** Allocate and copy structures containing a flexible array member dynamically
- **MEM34-C:** Only free memory allocated dynamically
- **MEM35-C:** Allocate sufficient memory for an object
- **MEM36-C:** Do not modify the alignment of objects by calling realloc()

Risk Assessment Summary

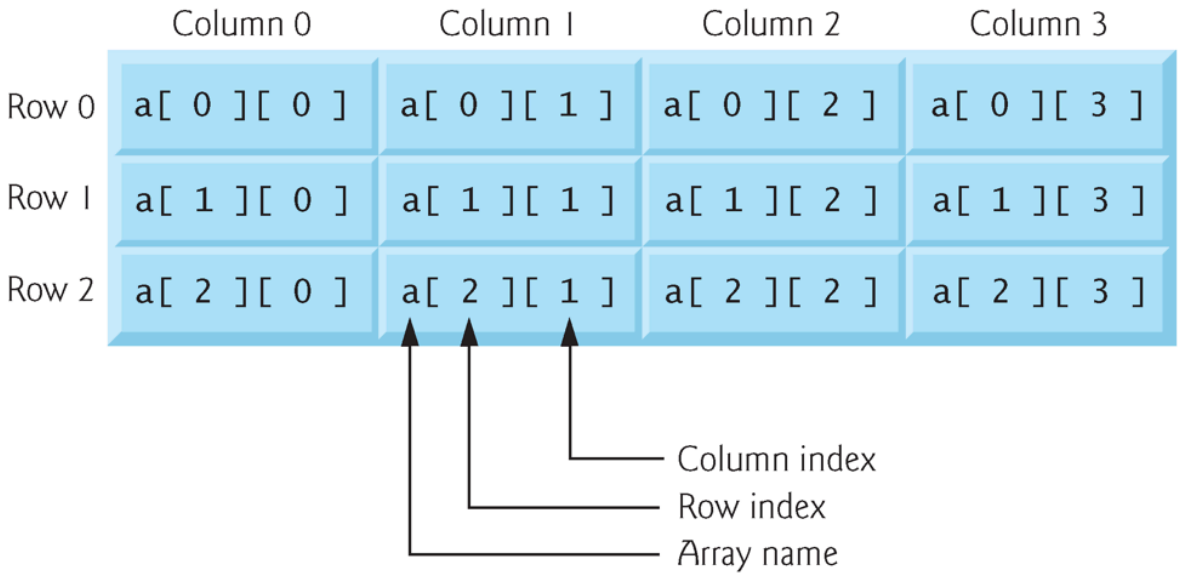
Rule	Severity	Likelihood	Remediation Cost	Priority	Level
MEM30-C	High	Likely	Medium	P18	L1
MEM31-C	Medium	Probable	Medium	P8	L2
MEM33-C	Low	Unlikely	Low	P3	L3
MEM34-C	High	Likely	Medium	P18	L1
MEM35-C	High	Probable	High	P6	L2
MEM36-C	Low	Probable	High	P2	L3

https://wiki.sei.cmu.edu/confluence/display/c/SEI+CERT+C+Coding+Standard

Dynamic data structures

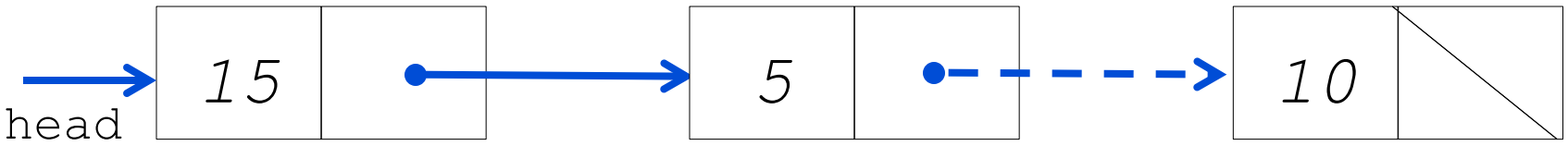
- We've studied fixed-size data structures such as **single-subscripted arrays**, **double-subscripted arrays** and **`structs`**

```
typedef struct account {
  unsigned short age;
  char name[100];
} accountt;

int main()
{
  int x[3];
  int a[3][4];
  accountt acount;
  return 0;
}
```



Dynamic data structures

- We've studied fixed-size data structures such as **single-subscripted arrays**, **double-subscripted arrays** and **`structs`**
- Dynamic data structures
  - They can **grow** and **shrink** during execution
- Linked lists
  - Allow **insertions** and **removals** anywhere in a linked list



Self-referential structures

- Self-referential structures
  - Structure that contains a pointer to a structure of the same type
  - Terminated with a NULL pointer (**0**)

```
typedef struct node {
   int data;
   struct node *nextPtr;
} nodet;
```

  - `nextPtr`
    - Points to an object of type node
    - Referred to as a link
    - Ties one **node** to another **node**
  - Can be linked together to form useful data structures such as **lists**, **queues**, **stacks** and **trees**

Not setting the link in the last node of a list to NULL can lead to runtime errors

Dynamic memory allocation

- Dynamic memory allocation
  - **Obtain** and **release** memory during execution
- `malloc`
  - Takes number of bytes to allocate
    - Use `sizeof` to determine the size of an object
  - Returns pointer of type `void *`
    - A `void *` pointer may be assigned to any pointer
    - If no memory available, returns `NULL`
  - Example: `nodet *newPtr = (nodet *)malloc(sizeof(nodet));`
- `free`
  - Always deallocates memory allocated by `malloc` to avoid **memory leak**
  - Takes a pointer as an argument
    - `free (newPtr);`

Dynamic memory allocation

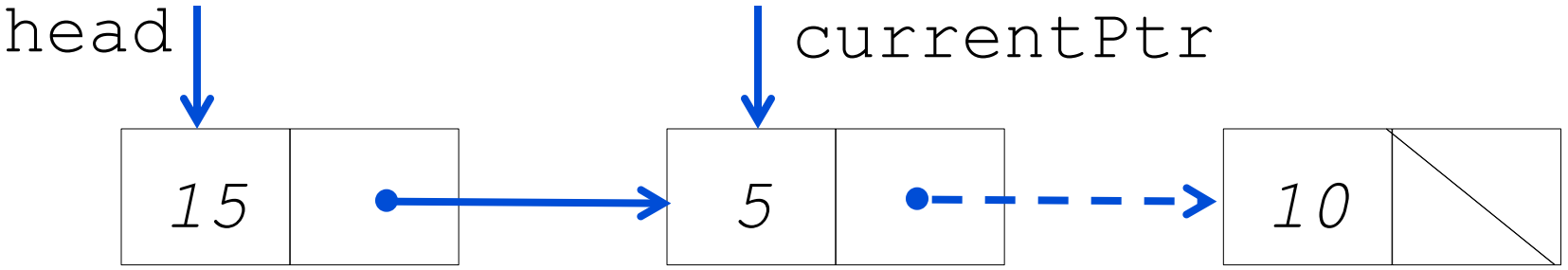
Two self-referential structures linked together


```
int main() {
  // allocates memory
  nodet *node1 = (nodet *)malloc(sizeof(nodet));
  nodet *node2 = (nodet *)malloc(sizeof(nodet));
  node1->data = 15;
  node2->data = 10;
  // link node1 to node2
  node1->nextPtr = node2;
  node2->nextPtr = NULL;
  // Deallocates memory allocated by malloc
  free(node1);
  free(node2);
  return 0;
}
```

If there exists no memory available, then `malloc` returns `NULL`

Linked lists properties

- Linked list
  - Linear collection of self-referential class objects, called nodes
  - Connected by pointer links
  - Accessed via a pointer to the first node of the list
  - Subsequent nodes are accessed via the link-pointer member of the current node
  - Link pointer in the last node is set to NULL to mark the list's end

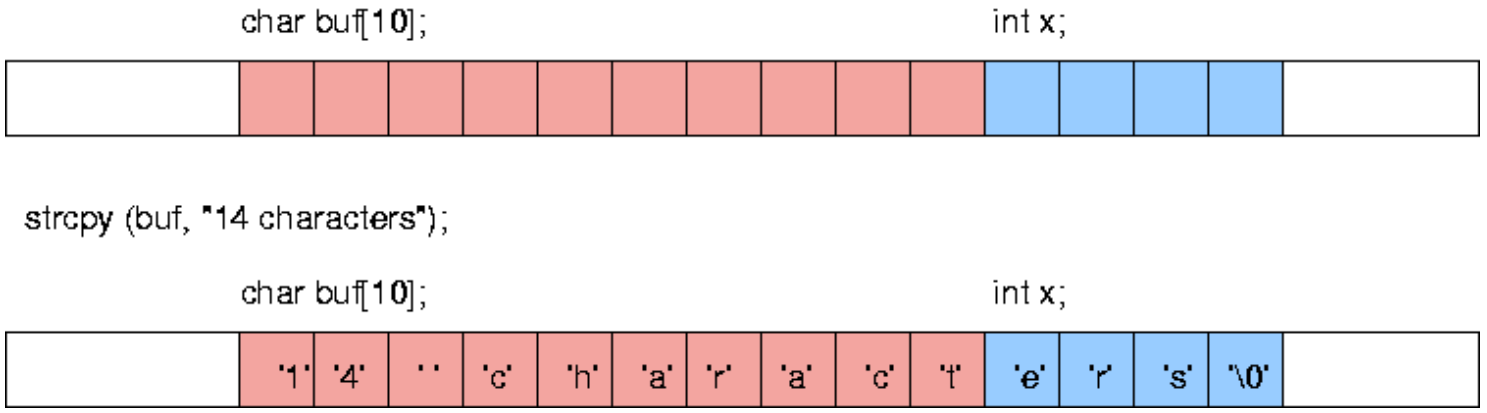


Linked lists properties

- Linked list
  - Linear collection of self-referential class objects, called nodes
  - Connected by pointer links
  - Accessed via a pointer to the first node of the list
  - Subsequent nodes are accessed via the link-pointer member of the current node
  - Link pointer in the last node is set to NULL to mark the list's end
- Use a **linked list** instead of an **array** when
  - You have an **unpredictable** number of elements
  - Your list needs to be **sorted quickly**

Linked lists properties

- Linked lists are **dynamic**, so the length of a list can **increase** or **decrease** as necessary
- Can we change the array size after compiling the program? What are the problems here?
  - **Arrays** can become **full**
    - An array can be declared to contain more elements than the number of data items expected, but this can waste memory



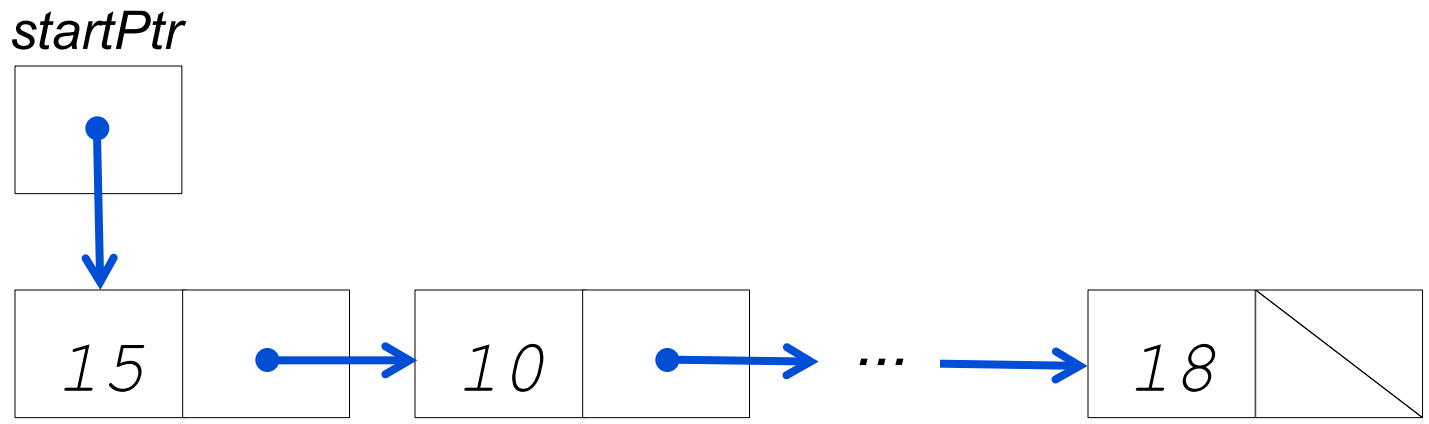
Linked lists properties

- Linked lists are **dynamic**, so the length of a list can **increase** or **decrease** as necessary
- Can we change the array size after compiling the program? What are the problems here?
  - **Arrays** can become **full**
    - An array can be declared to contain more elements than the number of data items expected, but this can waste memory
- **Linked lists** become **full** only when the system has **insufficient memory** to satisfy dynamic storage allocation requests
  - It can provide better **memory utilization**

Linked lists properties

- Linked-list nodes are **normally not stored contiguously in memory**
  - How arrays are stored in memory? What would be the advantage here?
    - This allows **immediate access** since the address of any element can be calculated directly based on its position relative to the beginning of the array
      - Linked lists do not afford such immediate access
- Logically, however, the nodes of a linked list appear to be contiguous
  - Pointers take up **space** and dynamic memory allocation incurs the **overhead of function calls**

A graphical representation of a linked list




```
int main() {
  …
  // link the nodes
  startPtr = node1;
  node1->nextPtr = node2;
  node2->nextPtr = node3;
  node3->nextPtr = NULL;
  …
  return 0;
}
```

Pointers should be initialised before they're used

A structure's size is not necessarily the sum of the size of its members (machine-dependent boundary alignment)

Error prevention when using linked lists

- If dynamically allocated memory is no longer needed, use `free` to return it to the system
  - Why must we set that pointer to `NULL`?
    - eliminate the possibility that the program could refer to memory that's been reclaimed and which may have already been allocated for another purpose
- Is it an error to free memory not allocated dynamically with `malloc`?
  - Referring to memory that has been freed is an error, which results in the program crashing **(double free)**

Exercise

- Fill in the blanks in each of the following:

a) A self- _____ structure is used to form dynamic data structures.

b) Function _____ is used to dynamically allocate memory.

c) A(n) _____ is a specialized version of a linked list in which nodes can be inserted and deleted only from the start of the list.

d) Functions that look at a linked list but do not modify it are referred to as _____.

e) Function _____ is used to reclaim dynamically allocated memory.

Illustrative example about linked lists

- We will show an example of linked list that manipulates a list of characters
- You can insert a character in the list in alphabetical order (function `insert`) or to delete a character from the list (function `delete`)

```c
// Fig. 12.3: fig12_03.c
// Inserting and deleting nodes in a list
#include <stdio.h>
#include <stdlib.h>

// self-referential structure
struct listNode {
   char data; // each listNode contains a character
   struct listNode *nextPtr; // pointer to next node
};

typedef struct listNode ListNode; // synonym for struct listNode
typedef ListNode *ListNodePtr; // synonym for ListNode*

// prototypes
void insert(ListNodePtr *sPtr, char value);
char delete(ListNodePtr *sPtr, char value);
int isEmpty(ListNodePtr sPtr);
void printList(ListNodePtr currentPtr);
void instructions(void);

int main(void)
{
```

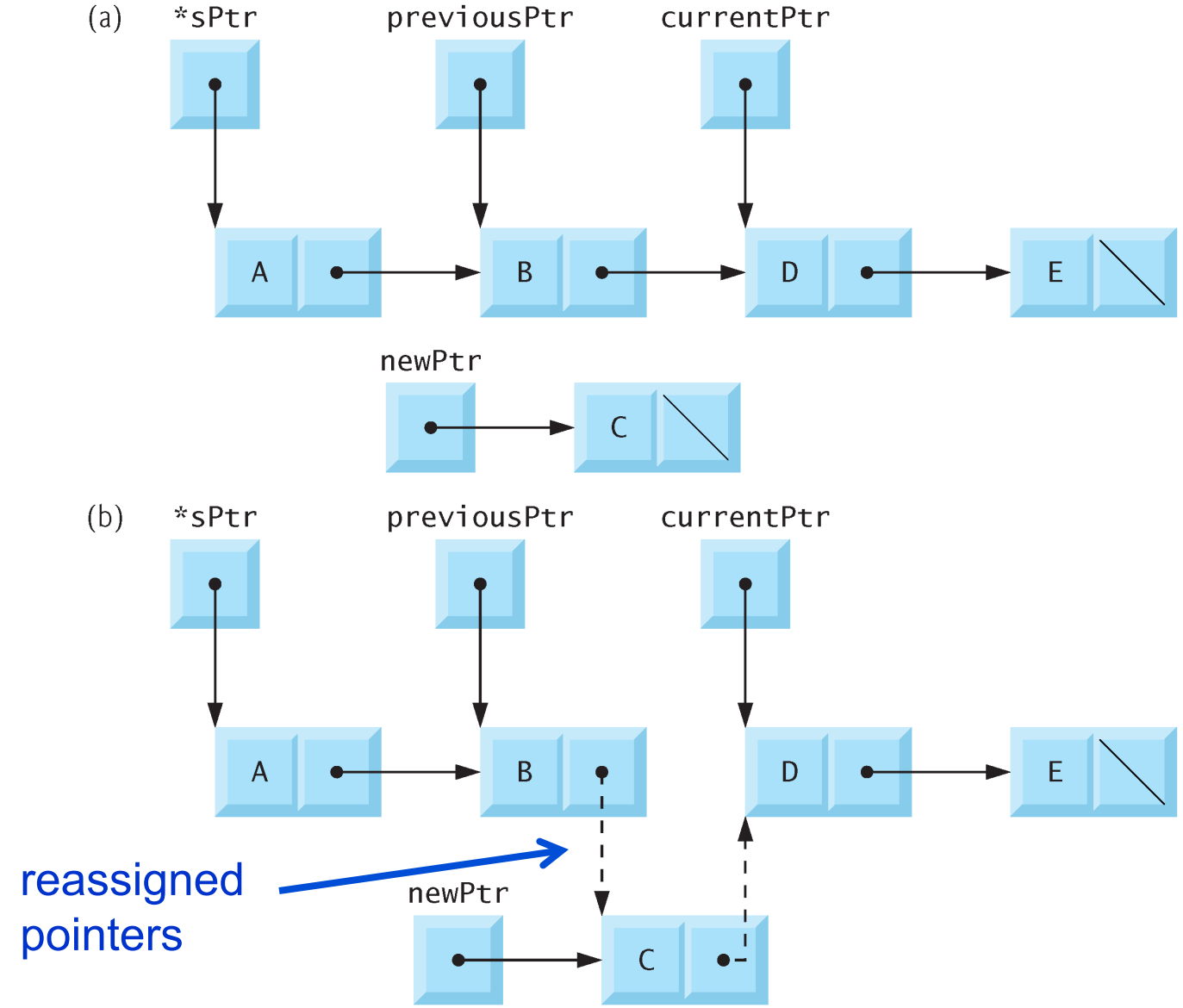
Inserting and deleting nodes in a list (Part 1 of 8)

```
24      ListNodePtr startPtr = NULL; // initially there are no nodes
25      char item; // char entered by user
26
27      instructions(); // display the menu
28      printf("%s", "? ");
29      unsigned int choice; // user's choice
30      scanf("%u", &choice);
31
32      // loop while user does not choose 3
33      while (choice != 3) {
34
35         switch (choice) {
36            case 1:
37               printf("%s", "Enter a character: ");
38               scanf("\n%c", &item);
39               insert(&startPtr, item); // insert item in list
40               printList(startPtr);
41               break;
42            case 2: // delete an element
43               // if list is not empty
44               if (!isEmpty(startPtr)) {
45                  printf("%s", "Enter character to be deleted: ");
46                  scanf("\n%c", &item);
47
```

Inserting and deleting nodes in a list (Part 2 of 8)

```
48                   // if character is found, remove it
49                   if (delete(&startPtr, item)) { // remove item
50                      printf("%c deleted.\n", item);
51                      printList(startPtr);
52                   }
53                   else {
54                      printf("%c not found.\n\n", item);
55                   }
56                }
57                else {
58                   puts("List is empty.\n");
59                }
60
61                break;
62             default:
63                puts("Invalid choice.\n");
64                instructions();
65                break;
66          }
67
68          printf("%s", "? ");
69          scanf("%u", &choice);
70       }
71
```

Inserting and deleting nodes in a list (Part 3 of 8)



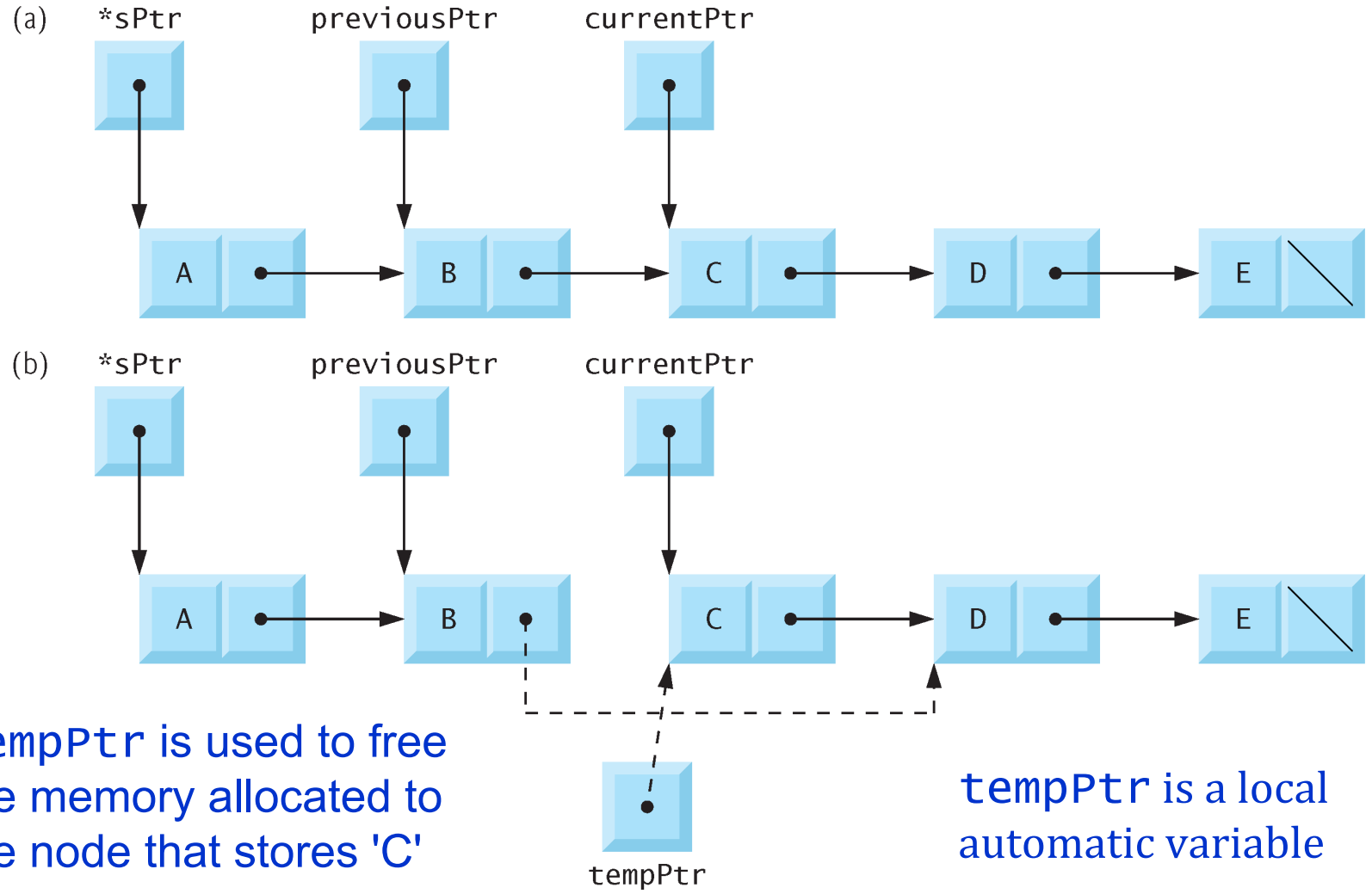
Inserting a node in order in a list

```
72       puts("End of run.");
73    }
74
75    // display program instructions to user
76    void instructions(void)
77    {
78       puts("Enter your choice:\n"
79          "   1 to insert an element into the list.\n"
80          "   2 to delete an element from the list.\n"
81          "   3 to end.");
82    }
83
84    // insert a new value into the list in sorted order
85    void insert(ListNodePtr *sPtr, char value)
86    {
87       ListNodePtr newPtr = malloc(sizeof(ListNode)); // create node
88
89       if (newPtr != NULL) { // is space available?
90          newPtr->data = value; // place value in node
91          newPtr->nextPtr = NULL; // node does not link to another node
92
93          ListNodePtr previousPtr = NULL;
94          ListNodePtr currentPtr = *sPtr;
95
```

Inserting and deleting nodes in a list (Part 4 of 8)

```
96          // loop to find the correct location in the list
97          while (currentPtr != NULL && value > currentPtr->data) {
98             previousPtr = currentPtr; // walk to ...
99             currentPtr = currentPtr->nextPtr; // ... next node
100         }
101
102         // insert new node at beginning of list
103         if (previousPtr == NULL) {
104            newPtr->nextPtr = *sPtr;
105            *sPtr = newPtr;
106         }
107         else { // insert new node between previousPtr and currentPtr
108            previousPtr->nextPtr = newPtr;
109            newPtr->nextPtr = currentPtr;
110         }
111      }
112      else {
113         printf("%c not inserted. No memory available.\n", value);
114      }
115   }
116
```

Inserting and deleting nodes in a list (Part 5 of 8)



tempPtr is used to free the memory allocated to the node that stores 'C'

tempPtr is a local automatic variable

Deleting a node from a list

```
117 // delete a list element
118 char delete(ListNodePtr *sPtr, char value)
119 {
120    // delete first node if a match is found
121    if (value == (*sPtr)->data) {
122       ListNodePtr tempPtr = *sPtr; // hold onto node being removed
123       *sPtr = (*sPtr)->nextPtr; // de-thread the node
124       free(tempPtr); // free the de-threaded node
125       return value;
126    }
127    else {
128       ListNodePtr previousPtr = *sPtr;
129       ListNodePtr currentPtr = (*sPtr)->nextPtr;
130
131       // loop to find the correct location in the list
132       while (currentPtr != NULL && currentPtr->data != value) {
133          previousPtr = currentPtr; // walk to ...
134          currentPtr = currentPtr->nextPtr; // ... next node
135       }
136
```

Inserting and deleting nodes in a list (Part 6 of 8)

```
137         // delete node at currentPtr
138         if (currentPtr != NULL) {
139            ListNodePtr tempPtr = currentPtr;
140            previousPtr->nextPtr = currentPtr->nextPtr;
141            free(tempPtr);
142            return value;
143         }
144      }
145
146      return '\0';
147   }
148
149   // return 1 if the list is empty, 0 otherwise
150   int isEmpty(ListNodePtr sPtr)
151   {
152      return sPtr == NULL;
153   }
154
```

Inserting and deleting nodes in a list (Part 7 of 8)

```
155 // print the list
156 void printList(ListNodePtr currentPtr)
157 {
158    // if list is empty
159    if (isEmpty(currentPtr)) {
160       puts("List is empty.\n");
161    }
162    else {
163       puts("The list is:");
164
165       // while not the end of the list
166       while (currentPtr != NULL) {
167          printf("%c --> ", currentPtr->data);
168          currentPtr = currentPtr->nextPtr;
169       }
170
171       puts("NULL\n");
172    }
173 }
```

Inserting and deleting nodes in a list (Part 8 of 8)

```
Enter your choice:
   1 to insert an element into the list.
   2 to delete an element from the list.
   3 to end.
? 1
Enter a character: B
The list is:
B --> NULL

? 1
Enter a character: A

The list is:
A --> B --> NULL

? 1
Enter a character: C
The list is:
A --> B --> C --> NULL

? 2
Enter character to be deleted: D
D not found.
```

Sample output for the program (Part 1 of 2)

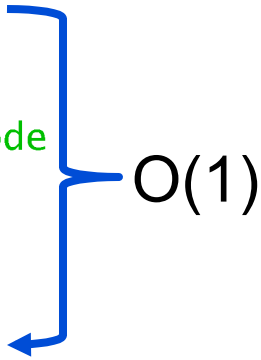
```
? 2
Enter character to be deleted: B
B deleted.
The list is:
A --> C --> NULL

? 2
Enter character to be deleted: C
C deleted.
The list is:
A --> NULL

? 2
Enter character to be deleted: A
A deleted.
List is empty.

? 4
Invalid choice.

Enter your choice:
   1 to insert an element into the list.
   2 to delete an element from the list.
   3 to end.
? 3
End of run.
```

Sample output for the program (Part 2 of 2)

Analysis of the linked list

OPERATION	RUNTIME (Big-O)
add to start of list	
add to end of list	
add at given index	
find an object	
remove first element	
remove last element	
remove at given index	
size	

```
72      puts("End of run.");
73   }
74
75   // display program instructions to user
76   void instructions(void)
77   {
78      puts("Enter your choice:\n"
79         "   1 to insert an element into the list.\n"
80         "   2 to delete an element from the list.\n"
81         "   3 to end.");
82   }
83
84   // insert a new value into the list in sorted order
85   void insert(ListNodePtr *sPtr, char value)
86   {
87      ListNodePtr newPtr = malloc(sizeof(ListNode)); // create node
88
89      if (newPtr != NULL) { // is space available?
90         newPtr->data = value; // place value in node
91         newPtr->nextPtr = NULL; // node does not link to another node
92
93         ListNodePtr previousPtr = NULL;
94         ListNodePtr currentPtr = *sPtr;
95
```



Analysis of the linked list (insert) – Part 1 of 2

```
96          // loop to find the correct location in the list
97          while (currentPtr != NULL && value > currentPtr->data) {
98             previousPtr = currentPtr; // walk to ...
99             currentPtr = currentPtr->nextPtr; // ... next node
100         }
101
102         // insert new node at beginning of list
103         if (previousPtr == NULL) {
104            newPtr->nextPtr = *sPtr;
105            *sPtr = newPtr;
106         }
107         else { // insert new node between previousPtr and currentPtr
108            previousPtr->nextPtr = newPtr;
109            newPtr->nextPtr = currentPtr;
110         }
111      }
112      else {
113         printf("%c not inserted. No memory available.\n", value);
114      }
115   }
116
```

O(n)

O(1)

Analysis of the linked list (insert) – Part 2 of 2

Insert -- runtime: O(1)+O(n)+O(1) = O(n)

```
117 // delete a list element
118 char delete(ListNodePtr *sPtr, char value)
119 {
120    // delete first node if a match is found
121    if (value == (*sPtr)->data) {
122       ListNodePtr tempPtr = *sPtr; // hold onto node being removed
123       *sPtr = (*sPtr)->nextPtr; // de-thread the node
124       free(tempPtr); // free the de-threaded node
125       return value;
126    }
127    else {
128       ListNodePtr previousPtr = *sPtr;
129       ListNodePtr currentPtr = (*sPtr)->nextPtr;
130
131       // loop to find the correct location in the list
132       while (currentPtr != NULL && currentPtr->data != value) {
133          previousPtr = currentPtr; // walk to ...
134          currentPtr = currentPtr->nextPtr; // ... next node
135       }
136
```

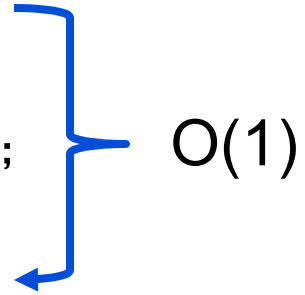
O(1)

O(1)

O(n)

Analysis of the linked list (delete) – Part 1 of 2

```
137         // delete node at currentPtr
138         if (currentPtr != NULL) {
139            ListNodePtr tempPtr = currentPtr;
140            previousPtr->nextPtr = currentPtr->nextPtr;
141            free(tempPtr);
142            return value;
143         }
144      }
145
146      return '\0';
147   }
148
149   // return 1 if the list is empty, 0 otherwise
150   int isEmpty(ListNodePtr sPtr)
151   {
152      return sPtr == NULL;
153   }
154
```



Analysis of the linked list (delete) – Part 2 of 2

Delete -- runtime: O(1)+O(n)+O(1) = O(n)

Analysis of the linked list

OPERATION	RUNTIME (Big-O)
add to start of list	O(*1*)
add to end of list	O(n)
add at given index	O(*n*)
find an object	O(*n*)
remove first element	O(*1*)
remove last element	O(n)
remove at given index	O(*n*)
size	O(1)

MEM30-C. Do not access freed memory

- Evaluating a **pointer into memory that has been deallocated** by a memory management function is **undefined behavior**
- Pointers to memory that has been deallocated are called **dangling pointers**. Accessing a dangling pointer can result in exploitable vulnerabilities
- According to the C Standard, using the value of a pointer that refers to space deallocated by a call to the free() or realloc() function is undefined behavior

Noncompliant Code Example

```
#include <stdlib.h>

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

void free_list(struct node *head) {
  for (struct node *p = head; p != NULL; p
= p->next) {
    free(p);
  }
}
```

Compliant Solution

```
#include <stdlib.h>

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

void free_list(struct node *head) {
  struct node *q;
  for(struct node *p=head; p!=NULL; p=q) {
    q = p->next;
    free(p);
  }
}
```

Risk Assessment

- Reading memory that has already been freed can lead to **abnormal program termination** and **denial-of-service attacks**
- Writing memory that has already been freed can additionally lead to the **execution of arbitrary code** with the permissions of the vulnerable process
- **Reading a pointer to deallocated memory** is **undefined behavior** because the pointer value is indeterminate and might be a trap representation

Rule	Severity	Likelihood	Remediation cost	Priority	Level
MEM30-C	High	Likely	Medium	P18	L1

MEM31-C. Free dynamically allocated memory when no longer needed

- Before the lifetime of the last pointer that stores the return value of a call to a standard memory allocation function has ended, it must be matched by a call to *free()* with that pointer value

Noncompliant Code Example

```
#include <stdlib.h>

enum { BUFFER_SIZE = 32 };

int f(void) {
  char *text_buffer=(char
*)malloc(BUFFER_SIZE);
  if (text_buffer == NULL) {
    return -1;
  }
  return 0;
}
```

Compliant Solution

```
#include <stdlib.h>

enum { BUFFER_SIZE = 32 };

int f(void) {
  char *text_buffer=(char
*)malloc(BUFFER_SIZE);
  if (text_buffer == NULL) {
    return -1;
  }

  free(text_buffer);
  return 0;
}
```

Risk Assessment

- Failing to free memory can result in the exhaustion of system memory resources, which can lead to a **denial-of-service attack**

Rule	Severity	Likelihood	Remediation cost	Priority	Level
MEM31-C	Medium	Probable	Medium	P8	L2

MEM33-C. Allocate and copy structures containing a flexible array member dynamically

- The C Standard, 6.7.2.1, paragraph 18 [ISO/IEC 9899:2011], says:

“As a special case, the last element of a structure with more than one named member may have an incomplete array type; this is called a flexible array member. In most situations, the flexible array member is ignored. In particular, the size of the structure is as if the flexible array member were omitted except that it may have more trailing padding than the omission would imply.”

Noncompliant Code Example

```
#include <stddef.h>

struct flex_array_struct {
  size_t num;
  int data[];
};

void func(void) {
  struct flex_array_struct flex_struct;
  size_t array_size = 4;
  /* Initialize structure */
  flex_struct.num = array_size;
  for (size_t i = 0; i < array_size; ++i) {
    flex_struct.data[i] = 0;
  }
}
```

Compliant Solution

```
#include <stdlib.h>
struct flex_array_struct {
  size_t num;
  int data[];
};
void func(void) {
  struct flex_array_struct *flex_struct;
  size_t array_size = 4;
  /* Dynamically allocate memory for the struct */
  flex_struct = (struct flex_array_struct *)malloc(
    sizeof(struct flex_array_struct)
    + sizeof(int) * array_size);
  if (flex_struct == NULL) {
    /* Handle error */
  }
```

Compliant Solution

```
  /* Initialize structure */
  flex_struct->num = array_size;

  for (size_t i = 0; i < array_size; ++i) {
    flex_struct->data[i] = 0;
  }
}
```

Risk Assessment

- Failure to use structures with flexible array members correctly can result in undefined behavior

Rule	Severity	Likelihood	Remediation cost	Priority	Level
MEM33-C	Low	Unlikely	Low	P3	L3

Secure C Programming

Chapter 8 of the CERT Secure C Coding Standard

- Chapter 8 of the CERT Secure C Coding Standard is dedicated to memory-management recommendations and rules—many apply to the uses of pointers and dynamic-memory allocation presented in this chapter.
- For more information, visit www.securecoding.cert.org.

Summary
(Secure C Programming)

- Pointers should not be left uninitialized
- They should be assigned either NULL or the address of a valid item in memory
- When you use free to deallocate dynamically allocated memory, the pointer passed to free is not assigned a new value, so it still points to the memory location where the dynamically allocated memory used to be

Summary
(Secure C Programming)

- Using a pointer that's been freed can lead to program crashes and security vulnerabilities
- When you free dynamically allocated memory, you should immediately assign the pointer either NULL or a valid address
- We chose not to do this for local pointer variables that immediately go out of scope after a call to free

Summary
(Secure C Programming)

- Undefined behavior occurs when you attempt to use free to deallocate dynamic memory that was already deallocated—this is known as a “double free vulnerability”
- To ensure that you don’t attempt to deallocate the same memory more than once, immediately set a pointer to NULL after the call to free—attempting to free a NULL pointer has no effect

Summary
(Secure C Programming)

- Function malloc returns NULL if it's unable to allocate the requested memory
- You should always ensure that malloc did not return NULL before attempting to use the pointer that stores malloc's return value