

Return to C

- Separate modules in C (i.e., ADTs)
- Dynamic memory (malloc, realloc, calloc)
- Arrays that grow in C
- Linked lists in C
- Trees in C

Abstract Data Types

- So far, we have described basic data types, all the standard C statements, operators and expressions, functions, and function prototypes.
- We want to introduce the concept of modularization
- Before there were object-oriented languages like Java and C++, users of imperative languages used **abstract data types** (ADT):
 - an abstract data type is a set of operations which access a collection of stored data
 - in Java and C++ this idea is called **encapsulation**

Abstract Data Types

- Since ANSI compilers support separate compilation of source modules, we can use abstract data types and function prototypes to **simulate modules**:
 - this is simply for convenience
 - a C compiler does not force us to use separate files
 - allows us to implement the “one declaration – one definition” rule

Abstract Data Types (2)

- For module "**mod**" there are two file
- **Interface module**: named "**mod.h**" contains function prototypes, public type definitions, constants, and when necessary declarations for global variables. Interface modules are also called header files.
 - Interface modules are accessed using the **#include** C preprocessor directive
- **Implementation module**: named "**mod.c**" contains the implementation of functions declared in the interface module.

Example: module bitstring

- **Module** `bitstring`
 - Interface module: `bitstring.h` contains the declarations for data structures and operations required to support bitstring manipulation. Contains items (i.e., types, functions) which **must** be visible to the user of the module.
 - Implementation module: `bitstring.c` contains implementation of bitstring operations

Interface Module: bitstring.h

```
#ifndef BITSTRING_H
#define BITSTRING_H

typedef unsigned int Uint;
typedef enum _bool { false = 0, true = 1 } bool;

#define BITSPERBYTE      8
#define ALLOCSIZE        (sizeof(Uint)* BITSPERBYTE)
#define BYTESPERAUNIT    (sizeof(Uint))

/* -- Bit Operations */

extern void clear_bits( Uint[], Uint );
extern void set_bit( Uint[], Uint );
extern void reset_bit( Uint[], Uint );
extern bool test_bit( Uint[], Uint );

#endif
```

Implementation Module: bitstring.c

```
#include "bitstring.h"

/* Clear a bit string */
void clear_bits( Uint bstr[], Uint naunits ) {
    Uint i;

    for ( i = 0; i < naunits; i++ )
        bstr[i] = 0;
}

/* Set a bit in a bit string */
void set_bit( Uint bstr[], Uint bit ) {
    Uint b_index = ( bit - 1 ) / ALLOCSIZE;
    Uint b_offset = ( bit - 1 ) % ALLOCSIZE;

    bstr[b_index] |= ( 1 << b_offset );
}
```

Implementation Module (2)

```
/* Reset a bit in a bit string */
```

```
void reset_bit( Uint bstr[], Uint bit ) {  
    Uint b_index = ( bit - 1 ) / ALLOCSIZE;  
    Uint b_offset = ( bit - 1 ) % ALLOCSIZE;  
  
    bstr[b_index] &= ~( 1 << b_offset );  
}
```

```
/* Determine the state of a bit in a bitstring */
```

```
bool test_bit( Uint bstr[], Uint bit ) {  
    Uint b_index = ( bit - 1 ) / ALLOCSIZE;  
    Uint b_offset = ( bit - 1 ) % ALLOCSIZE;  
  
    return( (bstr[b_index] & (1 << b_offset)) ? true : false );  
}
```


Using the Bitstring Module

```
#include "bitstring.h"

#define NUNITS 4

int main( int argc, char *argv[] ) {
    Uint set[NUNITS];

    clear_bits(set, NUNITS);
    set_bit(set, 8);
    set_bit(set, 12);

    if (test_bit(set, 12) == true)
        reset_bit(set, 12);

    return 0;
}
```

```
$ gcc module_user.c bitstring.c -o module_user
```

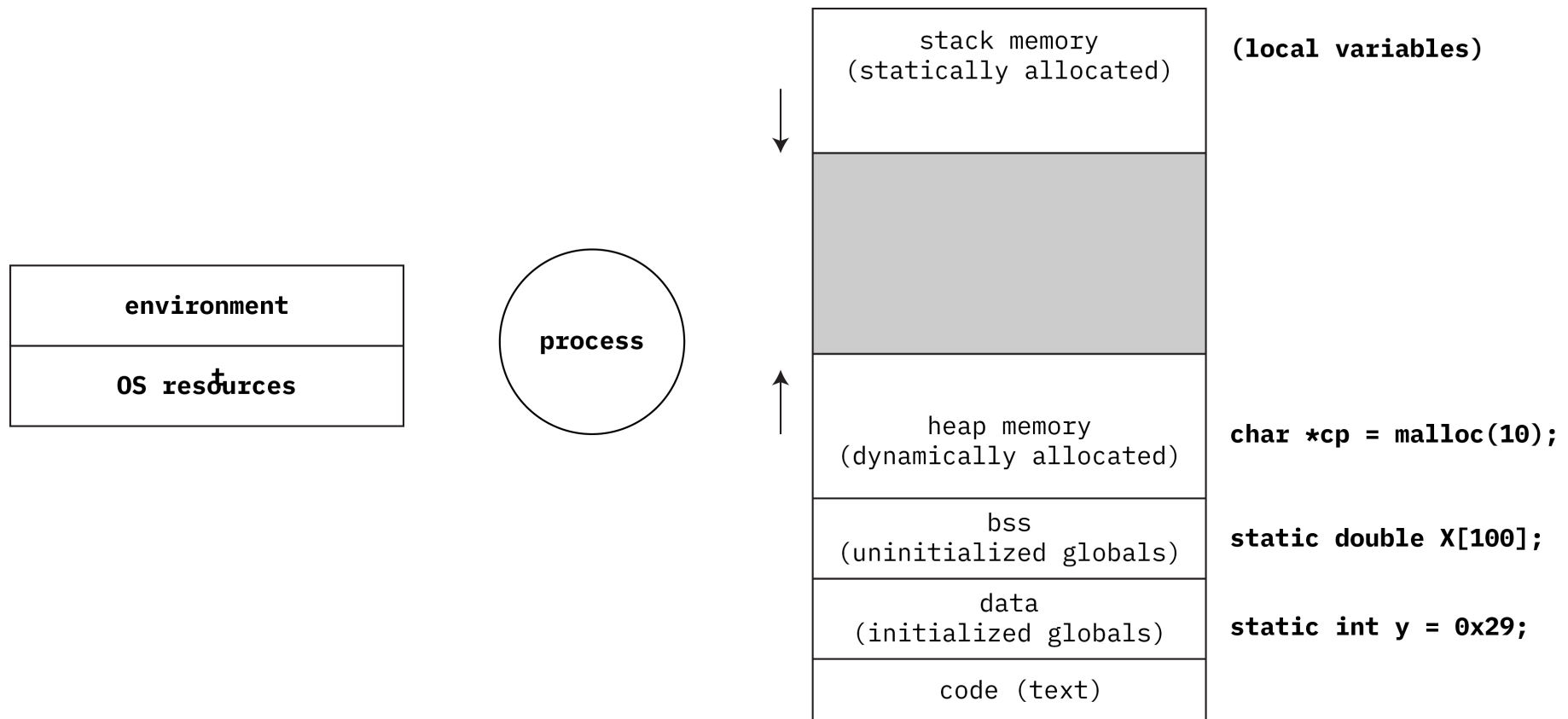
Dynamic memory in C

- The C memory model
- Managing the heap: `malloc()` and `free()`
- The void pointer and casting
- Memory leaks
- Applying the concepts:
 - **arrays that grow**
 - **linked lists**
 - **binary trees**
 - **hash maps**

C memory model

- Memory is divided into five segments: **uninitialized data**, **initialized data**, **heap**, **stack**, and **code**
- **Stack** is used to store **automatics** and activation records (stack frames) for functions
- Stack is located at the "top" of writable memory (high addresses)
- **Heap** stores explicitly requested memory which must be **dynamically allocated**
- Limits of heap and stack can bump into each other
- Initialized and uninitialized data located at at "top" of writable memory (high addresses)

C memory model



C memory model

- As the program executes, and function call-depth increases, the stack **grows downward**
- Similarly, as memory is explicitly requested for allocation, the heap **grows upward**
- Every time a function call is made, a new **stack frame** is created and memory allocated for variables to be used by the function
- Eventually, if stack and heap continue to grow, all memory available to the process will be exhausted and an **out of memory** condition will occur

Motivation for dynamic memory

- Memory must be allocated for storage before variables can be used, yet the amount might not be known at compile time
- Examples:
 - Reading records from a file in order to sort them, where file size is not known at time program is written
 - Constructing a list of "keywords" based on the content of some text file (whose size is unknown at compile time)
 - Representing a set as a linked list

Motivation for dynamic memory

- One solution: Write the program by hard-coding in the largest amount of memory that could possibly be needed
- Problem with this approach: Possibly occupies a large, unused area of memory if program-input sizes for most executions are almost always small
 - Note: virtual-memory systems mitigate the effects of this somewhat

Where to store what...

- Use **heap memory** for dynamic allocation when size is not known until run-time
- Use **stack memory** for parts where size is known at compile time
- Working with the stack is easy -- all variables are defined at compile time (no extra work for you)
- Working with the heap is a bit harder
 - In Java and Python, heap memory is automatically allocated to objects through use of the "new" keyword
 - Also in Java & Python, heap memory no longer used by a variable may be reclaimed for the system (**garbage collection**)

Heap memory in C

- Memory addresses in the heap are sometimes called **anonymous variables**
 - These variables do not have names like automatics and static variables
- **malloc()**: allocate dynamic memory
 - Takes a single parameter representing the **number of bytes of heap memory to be allocated**
 - **Returns a memory address** to the beginning of newly allocated block of memory
 - **If allocation fails, malloc()** returns NULL
- **#include <stdlib.h>** : contains function prototypes for malloc and related functions.

sizeof

- `sizeof()` is a macro that computes the number of bytes allocated for a specified type or variable (basic types, aggregate types)
- Use `sizeof()` to determine block size required by `malloc()`
- You must **always** check the value returned by `malloc()`!

```
int *a = malloc (sizeof(int));  
if (a == NULL) { /* error */ }  
  
struct datatype *dt = malloc (sizeof(struct datatype));  
if (dt == NULL) { /* error */ }  
  
char *buffer = malloc (sizeof(char) * 100);  
if (buffer == NULL) { /* error */ }
```

malloc() + casting

- Function prototype for malloc() :
 - `extern void *malloc(size_t n);`
 - `typedef unsigned int size_t;`
- The pointer returned is a generic pointer
- To use the allocated memory, we must **typecast** the returned pointer
 - Denoted by (`<sometype> *`)
 - Casting is a hint to the compiler (applies different typechecking to the block of memory after the typecast)

```
double *f = (double *) malloc (sizeof(double));
```

```
char *buf = (char *) malloc(100);
```

Casting

- What if we do not typecast?

```
double *f = malloc(sizeof(double));
```

```
<from some compilers>
```

```
warning: assignment makes pointer from  
double without a cast
```

- Always a good idea to cast
- Once heap memory is allocated:
 - It stays allocated for the duration of the program's execution...
 - ...unless it is **explicitly deallocated**.
 - All memory used in heap is returned to system when process/program terminates.

A family of functions

- There is more than just `malloc`:
 - `calloc`
 - `realloc`
 - `valloc`
- These serve slightly different purposes
 - One function both allocates and initializes the block of heap memory
 - One function adjusts heap structures to change size of a previously allocated block/chunk
 - One is now pretty much obsolete (i.e., meant to force allocation on some page boundary – which will make more sense in CSC 360)
- As we need these extra functions we'll trot them out

free()

- We use `free()` to return heap memory no longer needed back to the heap pool

```
extern void free( void * );
```

- `free()` takes a pointer to the allocated block of memory

```
void very_polite_function( int n )
{
    int *array = (int *) malloc (sizeof(int) * n);

    /* Code using the array */

    free (array);
}
```

Issues with dynamic memory

- A **memory leak** occurs when heap memory is **constantly allocated** but is **not freed** when no longer needed
- Memory leaks are almost always unintentional
 - Allocation and deallocation code locations are often widely separated.
 - Can be hard to find the memory-leak bug as it often depends upon the program running for a long time.
- Systems with automatic garbage collection (almost) never have memory leaks
 - Redundant memory is returned to heap for re-use
 - Downside: garbage collection is not always under control of the programmer
 - Also: some garbage collectors cannot reclaim some kinds of redundant instances of data types.

Arrays that grow

- All of our C programs using arrays to date have been static in size
 - Assignment specifications state the largest input size.
 - Memory is allocated for these arrays from the C compiler and run time
 - We never need to manage this memory.
- Arrays are very handy structure
 - Easy to index and access ($O(1)$ operations)
 - Contiguous block of memory can be exploited by other functions (qsort, memcpy).
- Therefore we would like to keep the convenience of arrays but also obtain the benefits of dynamic memory
 - ... and do so without having to write more complex structures like lists, heaps, etc.

Nameval array

- Suppose we wish to maintain an array of <name, value> pairs
 - Name is a string
 - Value is an integer
- We want to add new items to our array as they arrive
- If there is not enough room in the array, we want to grow it.
- To support this we'll keep the array's size and items-to-date associated with the array via a struct.
 - Note use of "typedef"

```
typedef struct Nameval Nameval;  
struct Nameval {  
    char    *name;  
    int     value;  
};
```

```
struct Nvtab {  
    int     nval;  
    int     max;  
    Nameval *nameval;  
} nvtab;  
  
enum { NVINIT = 1, NVGROW = 2 };
```

Creating a new nameval

```
Nameval *new_nameval(char *name, int value)
{
    Nameval *temp;

    temp = (Nameval *)malloc(sizeof(Nameval));
    if (temp == NULL) {
        fprintf(stderr, "Error mallocing a Nameval");
        exit(1);
    }

    /* temp->name == (*temp).name */
    temp->name = (char *)malloc((strlen(name)+1) * sizeof(char));
    if (temp->name == NULL) {
        fprintf(stderr, "Error mallocing a memory for string");
        exit(1);
    }
    strncpy(temp->name, name, strlen(name)+1);

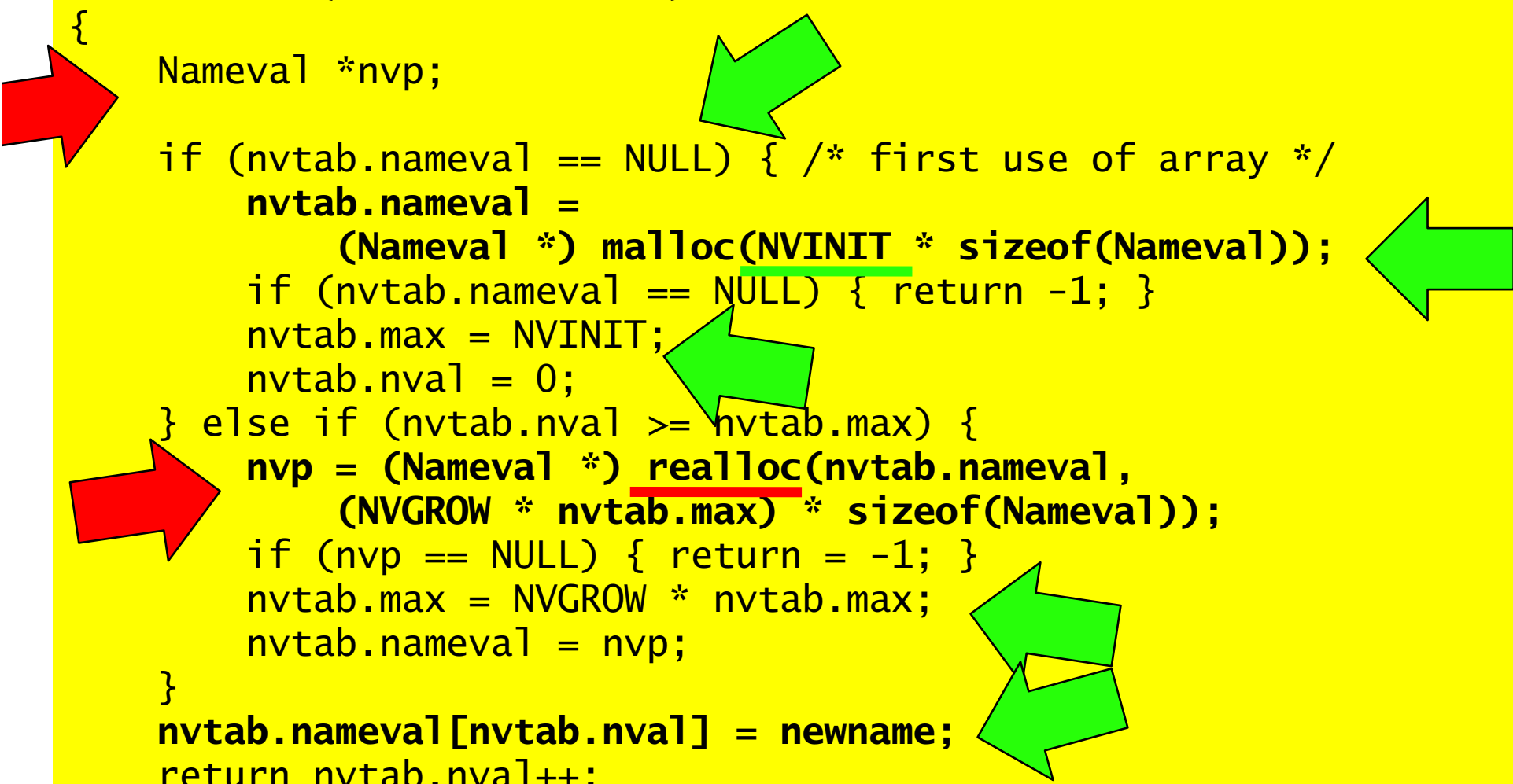
    temp->value = value;

    return temp;
}
```

addname

```
int addname(Nameval newname)
{
    Nameval *nvp;

    if (nvtab.nameval == NULL) { /* first use of array */
        nvtab.nameval =
            (Nameval *) malloc(NVINIT * sizeof(Nameval));
        if (nvtab.nameval == NULL) { return -1; }
        nvtab.max = NVINIT;
        nvtab.nval = 0;
    } else if (nvtab.nval >= nvtab.max) {
        nvp = (Nameval *) realloc(nvtab.nameval,
            (NVGROW * nvtab.max) * sizeof(Nameval));
        if (nvp == NULL) { return -1; }
        nvtab.max = NVGROW * nvtab.max;
        nvtab.nameval = nvp;
    }
    nvtab.nameval[nvtab.nval] = newname;
    return nvtab.nval++;
}
```



Deleting a name

- Arrays are contiguous...
 - Yet we may sometimes want to remove elements that are within the array
 - That is, neither at the start or end
- This can be tricky:
 - We need to decide what to do with the resulting gap in the array.
 - If element order doesn't matter: just swap last item in array with gap
 - If element order does matter (i.e., must be preserved), then we must move all the elements beyond the gap by one position

delname

```
int delname (char *name)
{
    int i;

    for (i = 0; i < nvtab.nval; i++) {
        if (strcmp(nvtab.nameval[i].name, name) == 0) {
            memmove(nvtab.nameval + i, nvtab.nameval + i + 1,
                    (nvtab.nval - (i + 1)) * sizeof(Nameval));
            nvtab.nval--;
            return 1;
        }
    }
    return 0;

    /* Note that no realloc is performed to resize the array.
     * Do you think this action is needed???
     */
}
```

Allocating memory for strings

```
/*
 * This doesn't solve our problem, but it does show how we use
 * malloc to allocate space for strings.
 *
 * This is sometimes built in to the C library as strdup().
 */

char *string_duplicator(char *input) {
    char *copy;

    assert (input != NULL);
    copy = (char *)malloc(sizeof(char) * strlen(input) + 1);
    if (copy == NULL) {
        fprintf(stderr, "error in string_duplicator");
        exit(1);
    }

    strncpy(copy, input, strlen(input)+1);
    return copy;
}
```

Chicken-and-egg...

- Consider this statement:
 - We must write our code **to be flexible for as many situations as possible...**
 - ... although this means we **cannot make some assumptions about input sizes.**
- Example:
 - For a file that processes text files, cannot make assumptions about the length of an input line
- Practical result:
 - Must (somehow) use malloc, realloc and possibly free appropriately
 - Safe alternative: `getline()`

getline() solution

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

int main(void)
{
    FILE *fp;
    char *line = NULL;
    size_t len = 0; /* size_t is really just an unsigned int */
    ssize_t read;   /* ssize_t is where a function may return a size or a
                     * negative number. */

    fp = fopen("/etc/motd", "r");
    if (fp == NULL) {
        exit(1);
    }

    while ((read = getline(&line, &len, fp)) != -1) {
        printf("Retrieved line of length %zu :\n", read);
        printf("%s", line);
    }

    if (line) {
        free(line);
    }
    exit(0);
}
```

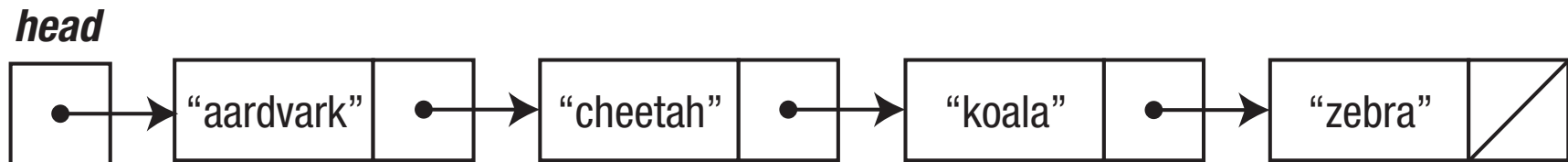

Lists

- While arrays are a convenient structure, they are not always the most suitable choice.
 - Arrays have a fixed size (albeit it may be resized with effort), yet a linked-list is exactly the size it needs to be to hold its contents.
 - Lists can be rearranged by changing a few pointers (which is cheaper than a block move like that performed by **memmove** in our implementation of **delname**)
 - When items are inserted or deleted from a list, the other items are not moved in memory.
 - If we store addresses to the **list elements** in some other data structure, the **list elements themselves** won't be necessarily be invalidated by changes to the **list**.

Lists

- So:
 - If the set of items we want to maintain changes frequently...
 - ... especially if the number of items is unpredictable...
 - then **a list is one good way to store them.**
- Typical usage of list for problem will dictate the kind of linked-list:
 - singly
 - singly, with head & tail pointers
 - doubly
 - circular
 - skip-list

Singly-linked list (no tail pointer)



- Set of four items
 - Each item has data (in this case a string) along with a pointer to the next item.
 - Head of the list is a pointer to the first item
 - End of the list is denoted by a NULL pointer.
 - Handful of operations (add new item to front; find a specific item; add new item before or after a specific item; perhaps delete item)

Other languages

- Some languages have lists built into their core
 - Python does this
 - As does Lisp, Scheme, F#, etc.
- Other languages implement lists via a library
 - C++
 - Java
 - C#
- Most of these languages have a List type
 - However, the approach (or idiom) in C is to start with the element type and then work outwards to the node.
 - That is, we are able to construct lists not via a list type but rather via a **node type**.

List node

- We'll revisit the same problem as described earlier (that of storing <name, value> pairs)
- The one addition to the Nameval struct is a "next" field
 - This field's type is a pointer to the node type Nameval
 - This is the usual style in C of declaring types for self-referencing structures.
 - We'll see more recursive structures later...

```
typedef struct Nameval Nameval;  
struct Nameval {  
    char    *name;  
    int     value;  
    Nameval *next; /* in list */  
};
```

Slight detour

- One of the tedious aspects of working with malloc is checking for success or failure
- We can accomplish this while still keeping our code clean by writing a small support function.
 - **emalloc**: a **wrapper function** that calls malloc; if allocation fails, it reports an error and exits the program.
 - Therefore we can use it as a memory allocator that never returns failure (but does terminate the program if there was an error).

```
void *emalloc(size_t n)
{
    void *p;

    p = malloc(n);
    if (p == NULL) {
        fprintf(stderr, "malloc of %u bytes failed", n);
        exit(1);
    }
    return p;
}
```

Constructing an item

- Before "creating a list", let us write a function that constructs an item.
 - It will allocate memory from the heap...
 - ... and then assign appropriate values to fields.
 - We will make heavy use of "->" syntax
 - We assume here that some other function has allocated memory for the name

```
Nameval *newitem (char *name, int value)
{
    Nameval *newp;

    newp = (Nameval *) emalloc(sizeof(Nameval));
    newp->name = name; /* Is this exactly what we want??? */
    newp->value = value;
    newp->next = NULL;
    return newp;
}
```

Adding an item to the front

- This is the simplest way to assemble a list
 - Also the fastest.
- This function (and others we'll write) all return a pointer to the first element as their function value
 - Note that this even works if the list is empty (e.g., pointing to NULL)

```
Nameval *addfront(Nameval *listp, Nameval *newp)
{
    newp->next = listp;
    return newp;
}
```

```
/* typical usage */
Nameval *nvlist = NULL;
...
Nameval *newnode = newitem(string_duplicator("Michael"), 50);
nvlist = addfront(nvlist, newnode);
```


Adding an item to the end

- With a singly-linked list this is an $O(n)$ operation
 - Traverse list until we reach the last node
 - Adjust that node's pointer to indicate the new node.
 - Note that the next field of node created by newitem is already set to NULL.

```
Nameval *addend(Nameval *listp, Nameval *newp)
{
    Nameval *p;

    if (listp == NULL) {
        return newp;
    }
    for (p = listp; p->next != NULL; p = p->next)
        ;
    p->next = newp;
    return listp;
}
```

```
...
Nameval *newnode = newitem(string_duplicator("Demetri"), 30);
nvlist = addend(nvlist, newnode);
```

Find an item

- As with adding to the end, we have an operation that is $O(n)$
 - Unlike a sorted array, binary search does not work on list.
 - However, the code is uncomplicated and its main loop is similar to that in addend.
- The function returns the node even though it is searching on the name
 - If the function succeeds, the return value will be a memory location on the list which can be dereferenced.
 - Otherwise the return value is NULL (i.e., the lookup failed)

```
Nameval *lookup(Nameval *listp, char *name)
{
    for ( ; listp != NULL; listp = listp->next) {
        if (strcmp(name, listp->name) == 0) {
            return listp;
        }
    }
    return NULL;
}
```

```
Nameval *t = lookup(nvlist, "Bobby");
if (t) {
    printf("%d\n", t->value);
} else {
    printf("Couldn't find the value\n");
}
```

An observation about lists

- Many other operations on list have a similar structure
 - Traverse through the list...
 - ... and while doing so, compute some value / perform some comparison / etc.
 - After traversing the list, return some value
- One approach is to write many such functions with this structure.
- Another approach is to write a more general-purpose function...
 - which traverses through the list...
 - ... and applies some function to each element in the list.
 - Let's call this function **apply**
 - It will take three arguments (the list; a function to be applied to each element on the list; and an argument for that function)

apply

```
/* apply: execute fn for each element of listp */  
  
void apply(Nameval *listp, void (*fn)(Nameval*, void*), void *arg)  
{  
    for ( ; listp != NULL; listp = listp->next) {  
        (*fn)(listp, arg); /* call the function */  
    }  
}
```

```
void (*fn)(Nameval*, void*),
```

Declare `fn` to be a pointer to a void-valued function (i.e., it is a variable that holds the address of a function that returns void).

Such a function takes two arguments: an address to a `Nameval` (list element) and a `void *` (a generic point to an argument for the function being passed in).

example: printing out all elements

```
/* apply: execute fn for each element of listp */  
  
void apply(Nameval *listp, void (*fn)(Nameval*, void*), void *arg)  
{  
    for ( ; listp != NULL; listp = listp->next) {  
        (*fn)(listp, arg); /* call the function */  
    }  
}  
  
void printnv(Nameval *p, void *arg)  
{  
    char *fmt;  
  
    fmt = (char *) arg;  
    printf(fmt, p->name, p->value);  
}
```

```
apply(nvlist, printnv, "%s: %x\n");
```

example: count of all elements

```
void inccounter(Nameval *p, void *arg)
{
    int *ip;

    /* p is not used -- all we care about is that this function
     * is called once per node.
     */
    ip = (int *)arg;
    (*ip)++;    /* Note the parentheses!!! */
}
```

```
int n;

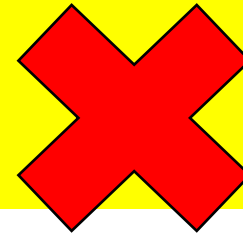
n = 0;
apply(nvlist, inccounter, &n);
printf("%d elements in nvlist\n", n);
```

Deleting elements from the list

- We have yet to see the use of **free** in the management of our lists
- Let's take the simplest case first: deleting the whole list
 - Here we must be rather careful
 - We cannot free an element if we need to dereference that same element later.
 - Also: **free** may itself modify the newly deallocated memory
- Must make good use of temporary variables

freeing the list

```
void bad_freeall(Nameval *listp)
{
    for ( ; listp != NULL; listp = listp->next ) {
        /* What is the value of listp->next after the next
         * operation?
         */
        free(listp);
    }
}
```



```
void freeall(Nameval *listp)
{
    Nameval *next;

    for ( ; listp != NULL; listp = next ) {
        next = listp->next;
        /* assume here the listp->name is freed someplace else */
        free(listp);
    }
}
```


Deleting elements from the list

- Deleting a single element requires more work than adding an element
 - Part of this is due to the consequences of using a singly-linked list.
 - It would be much easier with a doubly-linked list—but then again, such a list does require twice as many pointers to be maintained.
- This is the place where bugs are often introduced
 - Yet if we are careful—and correctly diagram what we intend to do—then we can get it right the first time.
 - Recall the two main cases: are we deleting the first element? or one past the first

Deleting a single element

```
Nameval *delitem (Nameval *listp, char *name)
{
    Nameval *curr, *prev;

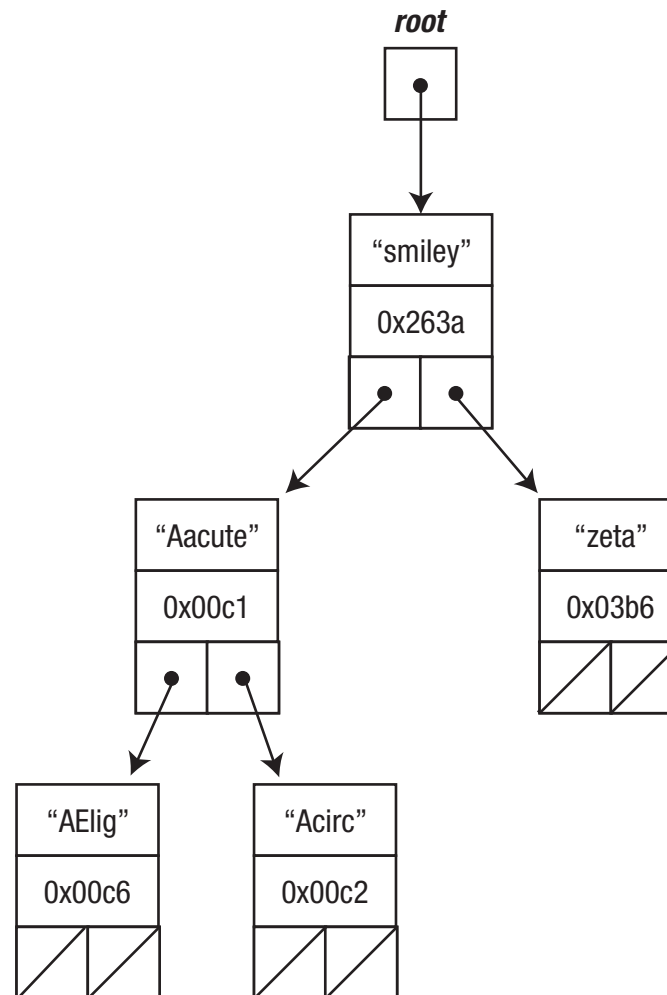
    prev = NULL;
    for (curr = listp; curr != NULL; curr = curr->next) {
        if (strcmp(name, curr->name) == 0) {
            if (prev == NULL) {
                listp = curr->next;
            } else {
                prev->next = curr->next;
            }
            free(curr);
            return listp;
        }
        prev = curr;
    }
    /* Ungraceful error handling, but gets the point across. */
    fprintf(stderr, "delitem: %s not in list", name);
    exit(1);
}
```

```
/* typical usage */
Nameval *nvlist = ...
... operations on list ...
nvlist = delitem(nvlist, "Boris");
```

Trees

- Hierarchical data structure
 - We use them implicitly when navigating through the Unix file system
 - Also used in compilers (e.g., parse trees)
 - We also construct trees programmatically to get $O(\lg n)$ behavior rather than $O(n)$ for our algorithms (after some assumptions)
- **Binary search tree**
 - Simpler tree flavour, straightforward to implement
 - Node in a binary search tree has a **value** and two pointers, **left** and **right**
 - The pointers lead to the node's children
 - All children to the left of a particular node have lower values than the node.
 - All children to the right of a particular node have greater values than the node.

Binary search tree example



Tree node

- We'll again re-use the same problem as shown earlier (<name, value> pairs are stored in nodes)
- We now need links to the left and right subtree
- Code to create such a node is left as an exercise.

```
typedef struct Nameval Nameval;  
struct Nameval {  
    char    *name;  
    int     value;  
    Nameval *left;  /* lesser */  
    Nameval *right; /* greater */  
};
```

Construction

- Although iterative node insertion is possible, we will focus on the recursive version
- Constructing a tree means descending into the tree recursively.
 - At insertion time, each new node ends up as a leaf node.
 - As other items are inserted later, a leaf node above a new leaf node will become the new node's parent.
- The algorithm must choose the left or right branch until the correct place for node is found.
 - But watch for how the left and right links are always updated!
- As with the linked-list routines, the insertion algorithm returns the root of the tree as the result.

Inserting node into tree

```
/* Assume newp has been already initialized. */
Nameval *insert(Nameval *treep, Nameval *newp)
{
    int cmp;

    if (treep == NULL) {
        return newp;
    }
    cmp = strcmp(newp->name, treep->name);
    if (cmp == 0) {
        fprintf(stderr, "insert: ignoring duplicate entry %s\n",
            newp->name);
    } else if (cmp < 0) {
        treep->left = insert(treep->left, newp);
    } else {
        treep->right = insert(treep->right, newp);
    }
    return treep;
}
```

```
Nameval *root = NULL;
...
Nameval *newNode = ... code to malloc a tree node, assign field values, etc. ...
...
root = insert(root, newNode);
```

Some observations

- The tree routines just shown do not permit duplicate entries.
- The insertion routine does not try to keep the tree balanced
 - It is possible that a sequence of inserts could yield a linear list instead of a tree (i.e., inserting a sequence of items that are already sorted).
 - However, this means our routines are a lot simpler (although it is not an oppressive amount of work to implement an AVL tree; rather, it is just a bit complicated!)
- The code for a lookup is similar to that for insertion
 - Recursively search by choosing the left or right subtrees
 - Return the correct node if matching lookup criteria, NULL otherwise.

lookup

```
Nameval *lookup(Nameval *treep, char *name)
{
    int cmp;

    if (treep == NULL) {
        return NULL;
    }
    cmp = strcmp(name, treep->name);
    if (cmp == 0) {
        return treep;
    } else if (cmp < 0) {
        return lookup(treep->left, name);
    } else {
        return lookup(treep->right, name);
    }
}
```

```
Nameval *temp;
temp = lookup(root, "Trudeau");
if (temp) {
    /* found it */
} else {
    /* NULL was returned;
}
```

Must be recursive?

- Both insert and lookup were recursive
 - The routines were defined in terms of themselves.
 - Base case: empty tree
 - Inductive step: left tree, then right tree
- However, not all recursive routines need be recursive
 - **Tail recursion:** when the recursive step (i.e., invocation of the recursive function) is the last step of the function
 - We can transform tail-recursive functions into iterative ones
 - All we require is some patching up of arguments (via assignments) and need a way to restart the body of the routine (via some loop)

Non-recursive lookup

```
Nameval *lookup(Nameval *treep,
char *name)
{
    int cmp;

    if (treep == NULL) {
        return NULL;
    }
    cmp = strcmp(name, treep->name);
    if (cmp == 0) {
        return treep;
    } else if (cmp < 0) {
        return lookup(treep->left,
            name);
    } else {
        return lookup(treep->right,
            name);
    }
}
```

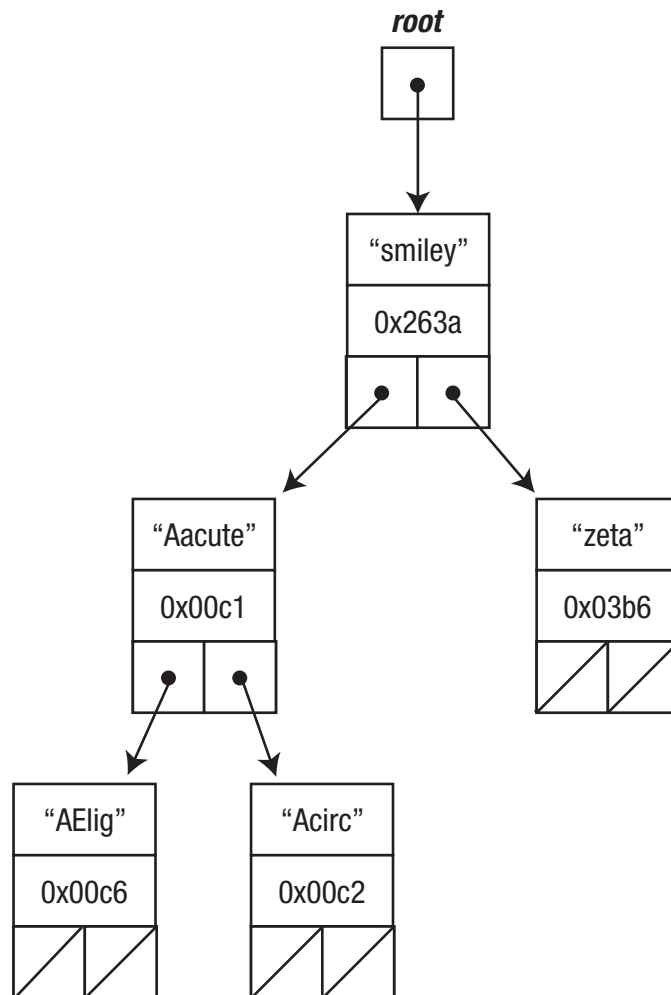
```
Nameval *nrlookup(Nameval *treep,
char *name)
{
    int cmp;

    while (treep != NULL) {
        cmp = strcmp(name, treep->name);
        if (cmp == 0) {
            return treep;
        } else if (cmp < 0) {
            treep = treep->left;
        } else {
            treep = treep->right;
        }
    }
    return NULL;
}
```

An observation about trees

- The same observations we made about operations on lists can also be made with respect to operations on trees
 - Traverse through the tree in some order
 - While doing so, compute some value / perform some comparison / etc.
 - After traversing the tree, return some value
- If we want to rewrite **apply** for a binary search tree, we must decide on some order
 - **inorder** traversal?
 - **pre-order** traversal?
 - **post-order** traversal?
- In effect we will have one **apply** function for each ordering, and each of these functions will take arguments similar to what we had for the list version of **apply**.

Binary search tree example



inorder:
AElig
Aacute
Acirc
smiley
zeta

post-order:
AElig
Acirc
Aacute
aeta
smiley

pre-order:
???

applyinorder

```
void applyinorder(Nameval *treep,
    void (*fn)(Nameval*, void*), void *arg)
{
    if (treep == NULL) {
        return;
    }
    applyinorder(treep->left, fn, arg);
    (*fn)(treep, arg);
    applyinorder(treep->right, fn arg);
}
```

```
/* We can even use some of the functions we passed as arguments
 * to the "list" version of apply!
 */
```

```
applyinorder(treep, printnv, "%s: %x\n");
```

```
/* Could you build a sort based on the tree routines +
 * a function (that you would write) given to applyinorder?
 */
```

Hash tables

- These combine:
 - arrays
 - lists
 - some mathematics
- Efficient structure for storing and retrieving dynamic data
- Typical application for hash tables: symbol tables
 - Associates some value (the **data**)...
 - with each member of a dynamic set of strings (the **keys**)
- Lots of places where hash tables are used

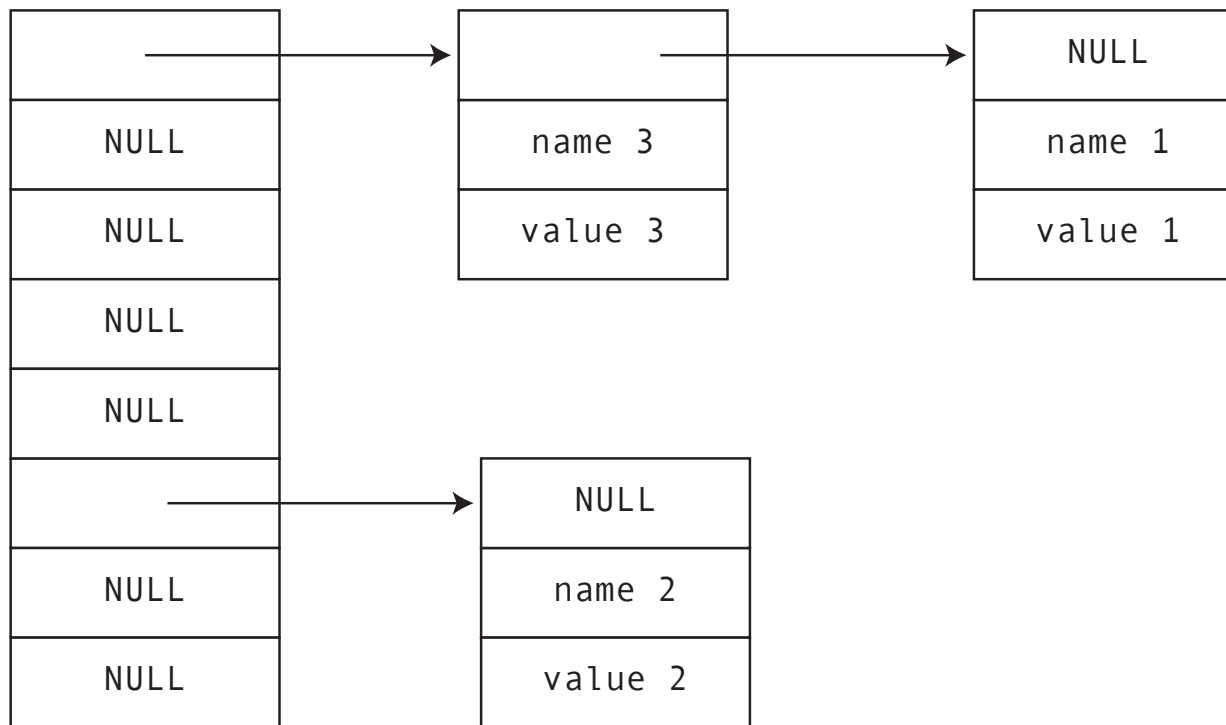
The idea

- Hash tables work on the following principle
 - Pass a key to the **hash function**
 - The hash function produces a **hash value**
 - These values will be **evenly distributed** through a modest-sized integer range
- The hash value is then used as an array index
 - In C the usual style is to associate each hash value / array index with a list of items that share the hash
 - Each such list (sometimes called a **hash chain**) is known as a **bucket**
- Collision handling:
 - Separate chaining (we'll use this)
 - Open addressing (linear or quadratic probing; ignore for now)

Example

syntab[NHASH]

hash chains



The practice

- Hash functions are pre-defined
- Array is sized appropriately (usually at compile time)
- Each element of the array is a list that **chains** together the items that share a hash value (i.e., hash chain)
- Equivalently:
 - A hash table of n items ...
 - ... is an array of lists whose average length is $(n/\text{array size})$
- Retrieving an item is an $O(1)$ operation provided the following two conditions hold:
 - we pick a good hash function
 - the lists do not grow too long

Element type

- A hash table is an array of lists...
 - ... therefore we can re-use the element type used for lists
- Maintaining individual hash chains is similar to maintaining individual lists
- Once we have a good hash function, the code falls out easily
 - just pick the hash bucket...
 - ... and walk along the list looking for a perfect match

```
typedef struct Nameval Nameval;  
struct Nameval {  
    char    *name;  
    int     value;  
    Nameval *next; /* in chain */  
};  
  
/* symbol table */  
Nameval *symtab[NHASH];
```

Lookup / insertion routine

- If item is found:
 - It is returned
- If item is not found and create flag is set:
 - add item to the table.

```
Nameval *lookup (char *name, int create, int value)
{
    int h
    Nameval *sym;

    h = hash(name);
    for (sym = symtab[h]; sym != NULL; sym = sym->next) {
        if (strcmp(name, sym->name) == 0) { return sym; }
    }
    if (create) {
        sym = (Nameval *) emalloc(sizeof(Nameval));
        sym->name = name; /* assumed allocated elsewhere */
        sym->value = value;
        sym->next = symtab[h];
        symtab[h] = sym;
    }
    return sym;
}
```

Why combine lookup & insertion?

- This is a common combination
- Without it we often duplicate effort
- (Without it the hash function to be executed twice for the same item.)
- This is a stylistic point (but one which can save a bit of tedium and reduce possibility of buggy code)

```
/*  
 * The code that might result if we  
 * keep lookup and insertion separate.  
 */  
  
if (lookup("name") == NULL) {  
    additem(newitem("name", value));  
}
```

Two more questions

- How big should the array be?
 - In general: make it large enough that each hash chain will have at most a few elements
 - Example: A compiler might have an array size of a few thousand
- How is the hash function computed?
 - Must be deterministic (i.e., produce same value each time for same key)
 - Must be fast
 - Must distribute data uniformly through the array
 - Lots of research exists that investigates these properties of hash functions

Possible hash function

- Common hashing algorithm for strings:
 - Build a value by adding each byte of the string to a multiple of the hash so far
 - Multiplication spreads bits from the new byte through the value so far
- Empirically: the values 31 and 37 have proven to be good choices for ASCII strings

```
#define MULTIPLIER 31

/* hash: compute hash value of string */
unsigned int hash (char *str) {
    unsigned int h;
    unsigned char *p;

    h = 0;
    for (p = (unsigned char *) str; *p != '\0'; p++) {
        h = MULTIPLIER * h + *p;
    }
    return h % NHASH;
}
```

Summary

- malloc() is an important tool
 - but it can be tricky at first to use correctly
 - is usually paired with free()
- dynamically-allocated memory needed for implementing many kinds of data structures
- two big takeaways
 - arrays can be resized (and that's handy as arrays are easy to use)
 - lists are used in many data structures (so it is important to know how to write routines that add to, traverse through, and remove from lists)

Colophon

- Some code examples are from "The Practice of Programming" (Addison-Wesley) © 1999 Brian W. Kernighan and Rob Pike