Lecture Notes for Lecture 11 of CS 5001 (Foundations of CS) for the Fall, 2018 session at the Northeastern University Silicon Valley Campus.

Memory Management

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Lecture 10 Review

- Defining types as aggregations of heterogeneous values allows modeling complex, real-world data about an entity.
- C provides a struct for creating aggregated types that are comprised of fields specified by variable declarations.
- Struct types have their own name space and require using ‘struct’ qualifier wherever instances of the type are defined
- Using typedef with struct eliminates the need for a ‘struct’ qualifier by putting the enum in the regular type name space.
- Initialize structs using positional or designated initializer lists.
- C makes “shallow copy” of a struct on assignment, when passing as a parameter, or returning from a function; avoid by using pointers.
- A struct can be embedded in another struct, or it can be shared by pointing to it from multiple other structs.

Memory Management

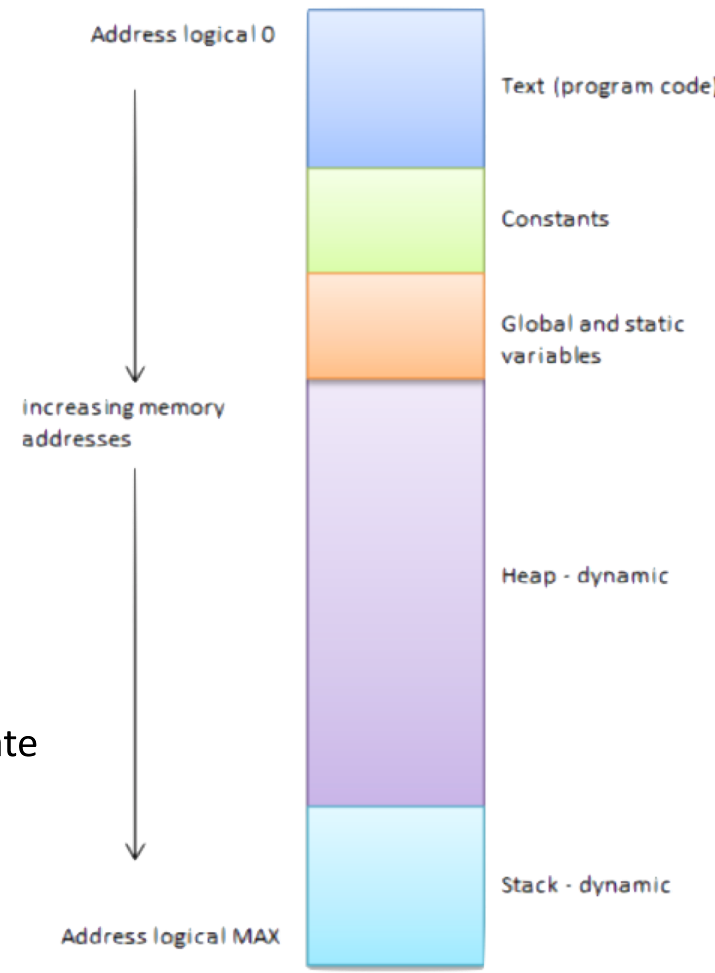
- In this lecture, we will learn about how memory is managed in a C program, including the local and global variables, constants, and the program code itself.
- We will also learn about functions that manage a special region of memory that is independent of global storage and the local storage within a given function.
- Finally, we will learn techniques for using this memory to create data, including arrays and structs, whose lifetime is under control of the programmer.

Memory Management

C Memory Management

- When a C program is loaded, it is organized into areas of memory, called segments:
  - Program Code
    - Compiled code for the program
  - Constants
    - Literal strings and other fixed constants
  - Global and static variables
    - Variables declared globally or statically
  - Dynamic memory (heap)
    - A pool of memory programmers can allocate
  - Local variables ("stack")
    - Storage for local variables in functions

C Program Memory Map



Memory Management

C Memory Management

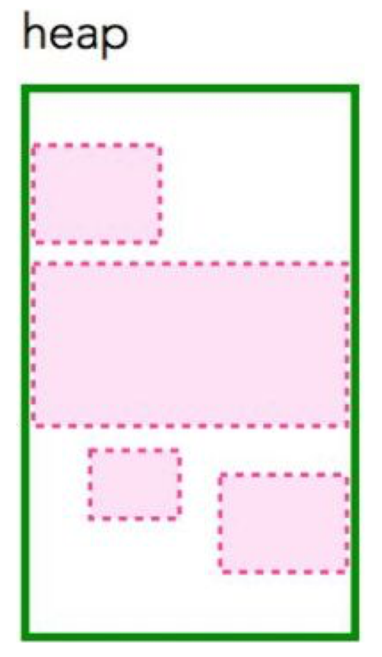
- Compiled program occupies memory in the *text segment*, and we can even have a pointer to a function in that area of memory.
- Literal strings and other constants are in a *literal segment* that cannot be modified, such as a pointer to a string literal.
- Global and static variables are automatically created in the *global segment*, which exist for as long as the program is running
- Local variables are automatically created in the *stack segment* when execution enters a function, and the storage automatically goes away when the function returns.
- The last area of memory is the *dynamic segment,* where programmers can allocate storage. What is it and how is it used?

Memory Management

What is Dynamic Memory?

- *Dynamic memory* is the storage in the dynamic segment. It is accessed through functions that manage the storage pool, sometimes referred to as the *heap*.

- A program can allocate a block of memory from the pool at runtime, use it for as long as it is needed, and then return the storage to the pool for reuse.



- The lifetime of local storage is a function call, and global storage lasts for the lifetime of the program, but the lifetime of dynamic memory is under program control.

Memory Management

Why Use Dynamic Memory?

- Local and global storage are useful when a fixed numbers of a type are required, whose lifetime is either the function or the lifetime of the program.
- With dynamic storage, arbitrary numbers of a type can be created whose lifetime transcends a function but is shorter than the lifetime of a program.
- Instances of a type can be created by a function at any point in a program, and then used by other functions until the instance is no longer needed.
- This makes creating instance of types in dynamic memory ideal when their lifetimes need to be under program control.

Memory Management

How is Dynamic Memory Used?

- Allocate dynamic memory using the standard C function *void *malloc(size_t nbytes)*, and free it using *void free(void *)*.
- Reference the allocated memory by assigning the pointer returned from *malloc* to a pointer of the type being allocated.
- Here is an example of allocating and, initializing the string, printing it, then returning the storage to the heap.

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

char *heapHello = malloc(strlen("hello")+1);            // allocate heap storage
strcpy(heapHello, "hello");                             // initialize allocated storage
printf("heapHello : \"%s\"\n", heapHello);              // print string
free(heapHello);                                        // return storage to heap
```

Memory Management

How is Dynamic Memory Used?

- Unlike local storage, heap storage remains active until it is returned to the heap by calling *free()*.
- The free() function can only be called with a pointer to storage that was allocated from the heap. A pointer to any other storage or to already freed storage is a runtime error.
- For convenience, the NULL pointer can be passed to free() and it performs no action. This is one of the few C functions with this property.

Memory Management

How is Dynamic Memory Used?

- Here is the standard C function *char *strdup(const char*)* that allocates, initializes, and returns a copy of a string.

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

/**
 * Allocates and initialize copy of str from dynamic memory.
 * @param str the string to copy
 * @return a copy of str from dynamic memory or NULL if str is NULL
 */
char *strdup(const char* str) {
    if (str == NULL) {
        return NULL;                    // special case NULL str
    }
    char *newstr = malloc(strlen(str)+1);     // allocate new string of same length
    return strcpy(newstr, str);               // copy to new string – strcpy returns newstr

    //    return str == NULL ? NULL : strcpy(malloc(strlen(str)+1), str);
}
```

Memory Management

How is Dynamic Memory Used?

- The storage for the string copy returned by *strdup()* must be returned to the heap by calling *free()* on the returned pointer.
- Once allocated storage is returned, it can no longer be accessed.

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

/** Test strdup function */
int main(void) {
    char *heapHello = strdup("hello");              // allocate and initialize string ”hello”
    printf("heapHello : \"%s\"\n", heapHello);      // print string
    free(heapHello);                                // return storage to heap
    char *heapNULL = strdup(NULL);                  // allocation and initialize NULL string
    printf("heapNULL : \"%s\"\n", heapNULL);        // print string
    free(heapNULL);                                 // return storage to heap
}
```

Memory Management

How is Dynamic Memory Used?

- The size of the memory allocated from the heap is only guaranteed to be the requested size. The standard C function *void* realloc(void*)* can be used to resize it.
- If necessary, the content of the previously allocated storage is copied to new storage and the previous storage is freed.

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

char *heapHello = malloc(strlen("hello")+1);          // allocate heap storage
strcpy(heapHello, "hello");                           // initialize allocated storage
printf("heapHello : \"%s\"\n", heapHello);            // print string

heapHello = realloc(strlen("hello world")+1);         // extend allocated storage
strcat(heapHello, " world");                          // append to extended storage
printf("heapHello : \"%s\"\n", heapHello);            // print string
free(heapHello);                                      // return storage to heap
```

Memory Management

Example: Allocating Journal Struct

- Any C type can allocated in dynamic memory. Here is an example of allocating a Journal struct from dynamic storage:

```
/** Typedef for ISSN: nnnn-nnnN */
typedef uint32_t Issn;

/** Struct that defines a Publisher */
typedef struct {        // “anonymous struct”
    char name[100];         // name of publisher
} Publisher;            // only known by its typedef name

/** Struct that defines a Journal */
typedef struct {        // “anonymous struct”
    char name[100];         // journal name
    Issn issn;              // defined type for the ISSN of journal
    Publisher publisher;    // defined type for the journal publisher
} Journal;              // only known by its typedef name
```

Memory Management

Example: Allocating Journal Struct

```
/**
 * Get string representation of ISSN.
 * @param issn the ISSN value
 * @param issnChars array to receive the ISSN characters
 * @return pointer to ISSN chars
 */
char *issnToString(Issn issn, char issnChars[]) {
    // make use of underlying uint32_t type of ISSN internally
    sprintf(issnChars, "%04x-%04x", issn >> 16, issn & 0xFFFF);
    if (issnChars[8] == 'a') {
        issnChars[8] = 'X';  // issn uses ‘X’ rather than ‘a’ for 10 for check digit
    }
    return issnChars;
}
```

Memory Management

Example: Allocating Journal Struct

```
/**
 * Print a Journal.
 * @param journal the journal to print
 */
void printJournal(const Journal *journal) {
    char issnChars[10];
    char* issnString = issnToString(journal->issn, issnChars);
    printf(”journal name: '%s'\nISSN: %s\npublisher name: '%s'\n",
            journal->name, issnString, journal->publisher.name);
}
```

Memory Management

Example: Allocating Journal Struct

```
/** Create a new Journal.
  * @param name the journal name
  * @param issn the journal issn
  * @param pubName the publisher name
  * @return the new journal
  */
Journal *newJournal(const char *name, Issn issn, const char *pubName) {
    Journal *journal = malloc(sizeof(Journal));
    strcpy(journal->name, name);
    journal->issn = issn;
    strcpy(journal->publisher.name, pubName);
    return journal;
}

/** Delete the journal
 * @param journal the journal to delete
 */
void deleteJournal(Journal *journal) {
    free(journal);
}
```

Memory Management

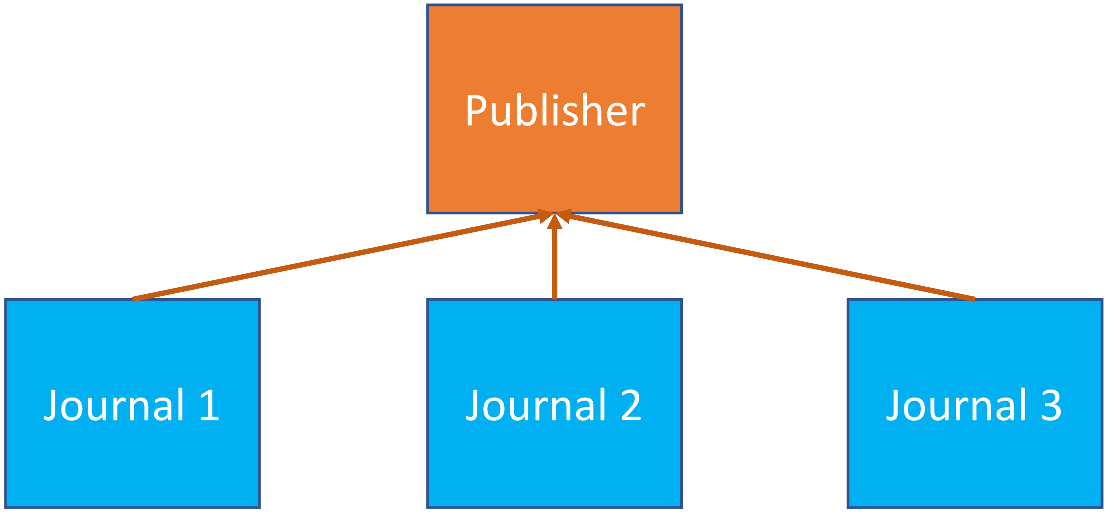
Example: Allocating Journal Struct

```
/** Test dynamic allocation of journal */
int main(void) {
    const char *ngs = "National Geographic Society";

    Journal *nationalGeographic =
        newJournal("National Geographic", 0x00279358, ngs);
    Journal *nationalGeographicExplorer =
        newJournal("National Geographic Explorer", 0x15413357, ngs);
    Journal *nationalGeographicKids =
        newJournal("National Geographic Kids", 0x15423042, ngs);

    printJournal(nationalGeographic);
    printJournal(nationalGeographicExplorer);
    printJournal(nationalGeographicKids);

    deleteJournal(nationalGeographic);
    deleteJournal(nationalGeographicExplorer);
    deleteJournal(nationalGeographicKids);
}
```

Memory Management

Example: One-To-Many Unidirectional Relationship

- We also looked at having the Publisher field point to its publisher, so that journals can share a publisher struct.
- This is *one-to-many relationship*, and is often notated as 1:* to show that one publisher can have 0 or more journals. It is *unidirectional* because the Publisher does not point back.



Memory Management

Example: One-To-Many Unidirectional Relationship

- We also looked at making the Publisher field point to its publisher, so that many journals can share a publisher struct.

```
/** Typedef for ISSN: nnnn-nnnN */
typedef uint32_t Issn;

/** Struct that defines a Publisher */
typedef struct {        // “anonymous struct”
    char name[100];         // name of publisher
} Publisher;            // only known by its typedef name

/** Struct that defines a Journal */
typedef struct {        // “anonymous struct”
    char name[100];         // journal name
    Issn issn;              // defined type for the ISSN of journal
    Publisher *publisher;   // defined type for the journal publisher
} Journal;              // only known by its typedef name
```

Memory Management

Example: One-To-Many Unidirectional Relationship

```
/**
 * Print a Publisher.
 * @param publisher the publisher to print
 */
void printPublisher(const Publisher *publisher) {
    printf(”publisher name: ’%s’\n”, publisher->name);
}

/**
 * Print a Journal.
 * @param journal the journal to print
 */
void printJournal(const Journal *journal) {
    char issnChars[10];
    char* issnString = issnToString(journal->issn, issnChars);
    printf(”journal name: '%s'\nISSN: %s\n",  journal->name, issnString);
    printPublisher(journal->publisher);  // journal publisher pointer field
}
```

Memory Management

Example: One-To-Many Unidirectional Relationship

```
/**
  * Create a new Publisher.
  * @param name the publisher name
  */
Publisher *newPublisher(const char *name) {
    Publisher *publisher = malloc(sizeof(Publisher));
    strcpy(publisher->name, name);
    return publisher;
}

/**
 * Delete the publisher
 * @param publisher the publisher to delete
 */
void deletePublisher(Publisher *publisher) {
    free(publisher);
}
```

Memory Management

Example: One-To-Many Unidirectional Relationship

```
/** Create a new Journal.
  * @param name the journal name
  * @param issn the journal issn
  * @param pubName the publisher name
  */
Journal *newJournal(const char *name, Issn issn, Publisher *publisher) {
    Journal *journal = malloc(sizeof(Journal));
    strcpy(journal->name, name);
    journal->issn = issn;
    journal->publisher = publisher;
    return journal;
}

/** Delete the journal
 * @param journal the journal to delete
 */
void deleteJournal(Journal *journal) {
    free(journal);
}
```

Memory Management

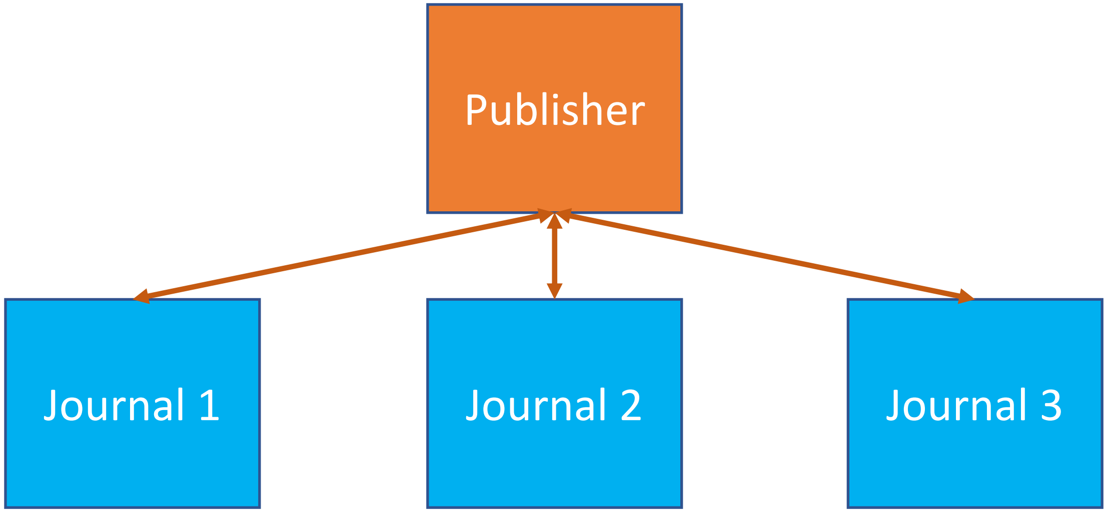
Example: One-To-Many Unidirectional Relationship

```
/** Test dynamic allocation of publisher and journal */
int main(void) {
    Publisher *ngs = newPublisher("National Geographic Society");

    Journal *nationalGeographic =
        newJournal("National Geographic", 0x00279358, ngs);
    Journal *nationalGeographicExplorer =
        newJournal("National Geographic Explorer", 0x15413357, ngs);
    Journal *nationalGeographicKids =
        newJournal("National Geographic Kids", 0x15423042, ngs);

    printJournal(nationalGeographic);
    printJournal(nationalGeographicExplorer);
    printJournal(nationalGeographicKids);

    deleteJournal(nationalGeographic);
    deleteJournal(nationalGeographicExplorer);
    deleteJournal(nationalGeographicKids);
    deletePublisher(ngs);
}
```

Memory Management

Example: One-To-Many Bidirectional Relationship

- We can make the relationship *bidirectional* by also having the Publisher also point to its Journals.
- Given a Journal, we can locate its Publisher, and given a Publisher, we can locate all of its Journals.



Memory Management

Example: One-To-Many Bidirectional Relationship

- The easiest way to point to the journals is to add an array of Journal pointers to the Publisher. When creating a Journal, we must also add a pointer to it in the *journals* array.
- How do we determine the *journals* array index? The easiest way is to also add a *nJournals* field with the current number of journals, and use it as the index of the next journal entry.

```
/** Struct that defines a Journal */
typedef struct {        // "anonymous struct"
    char name[100];             // name of publisher
    Journal *journals[10]       // up to 10 journals
    unsigned int nJournals;     // number of journals
} Publisher;            // only known by its typedef name
```

Memory Management

Example: One-To-Many Bidirectional Relationship

- Because Journal has a Publisher* field and Publisher now has a Journal* array field, the circular reference must be resolved.
- The solution is to add a *forward declaration* of the Journal struct and typedef before the Publisher definition. This works because Publisher points to rather than embeds a Journal.

```
/** Forward declaration of Journal struct and typedef */
typedef struct Journal Journal;      // cannot omit struct name
    …
/** Struct that defines Journal */
typedef struct Journal {   // struct required, but repeating typedef ok too
    ….
} Journal;
```

Memory Management

Example: One-To-Many Unidirectional Relationship

```
/**
  * Create a new Publisher.
  * @param name the publisher name
  */
Publisher *newPublisher(const char *name) {
    Publisher *publisher = malloc(sizeof(Publisher));
    strcpy(publisher->name, name);
    publisher->nJournals = 0;      // initially no journals
    return publisher;
}

/**
 * Delete the publisher.
 * @param publisher the publisher to delete
 */
void deletePublisher(Publisher *publisher) {
    free(publisher);
}
```

Memory Management

Example: One-To-Many Unidirectional Relationship

```
/**
 * Add a journal to a publisher.
 * @param publisher the publisher
 * @param journal the journal to add
 */
void addJournalToPublisher(Publisher *publisher, Journal *journal) {
    assert(publisher->nJournals < 10);  // program exits if too many journals
    publisher->journals[publisher->nJournals++] = journal;
}
```

Memory Management

Example: One-To-Many Bidirectional Relationship

- Prints only the publisher and the journal information.

```
/**
 * Print a Publisher.
 * @param publisher the publisher to print
 */
void printPublisherInfo(const Publisher *publisher) {
    printf(”publisher name: ’%s’\n”, publisher->name);
}
/**
 * Print a Journal only without publisher info.
 * @param journal the journal to print
 */
void printJournalInfo(const Journal *journal) {
    char issnChars[10];
    char* issnString = issnToString(journal->issn, issnChars);
    printf("journal name: '%s'\nISSN: %s\n", journal->name, issnString);
}
```

Memory Management

Example: One-To-Many Bidirectional Relationship

- This function prints the journal with its publisher info.

```
/**
 * Print a Journal and its publisher
 * @param journal the journal to print
 */
void printJournal(const Journal *journal) {
    printJournalInfo(journal);
    printPublisherInfo(journal->publisher);
}
```

Memory Management

Example: One-To-Many Bidirectional Relationship

- This function prints the publisher with its journals info.

```
/**
 * Print a Publisher and its journals.
 * @param publisher the publisher to print
 */
void printPublisher(const Publisher *publisher) {
    printPublisherInfo(publisher);

    for (int jnl = 0; jnl < publisher->nJournals; jnl++) {
        printJournalInfo(publisher->journals[jnl]);
    }
}
```

Memory Management

Example: One-To-Many Bidirectional Relationship

```
/**
 * Create and initialize a journal for a publisher.
 * @param name the journal name
 * @param issn the journal issn
 * @param publisher the journal publisher
 * @return the journal
 */
Journal *newJournal(const char *name, Issn issn, Publisher *publisher) {
    Journal *journal = malloc(sizeof(Journal));
    strcpy(journal->name, name);
    journal->issn = issn;
    journal->publisher = publisher;

    addJournalToPublisher(publisher, journal);
    return journal;
}
```

Memory Management

Example: One-To-Many Bidirectional Relationship

```
/**
 * Delete the journal.
 * @param journal the journal to delete
 */
void deleteJournal(Journal *journal) {
    free(journal);
}
```

Memory Management

Example: One-To-Many Bidirectional Relationship

```
/** Test dynamic allocation of publisher and journal */
int main(void) {
    Publisher *ngs = newPublisher("National Geographic Society");

    Journal *nationalGeographic =
          newJournal("National Geographic", 0x00279358, ngs);
    Journal *nationalGeographicExplorer =
          newJournal("National Geographic Explorer", 0x15413357, ngs);
    Journal *nationalGeographicKids =
          newJournal("National Geographic Kids", 0x15423042, ngs);
```

Memory Management

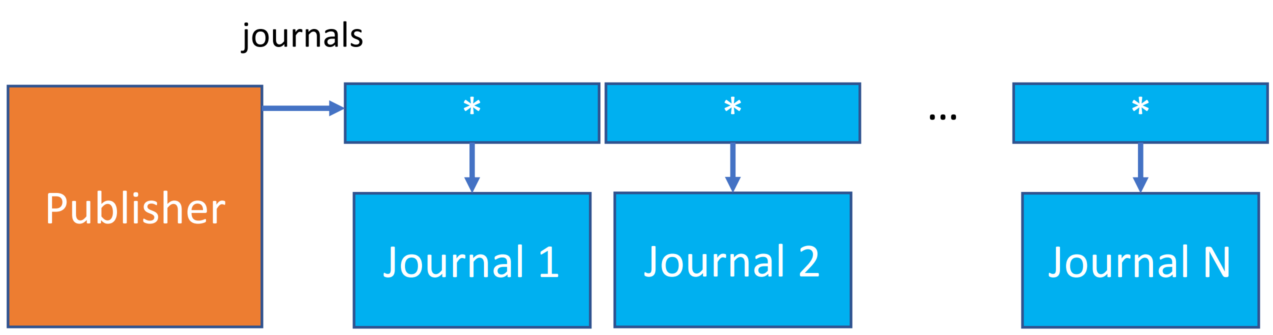
Example: One-To-Many Bidirectional Relationship

```
    printJournal(nationalGeographic);
    printJournal(nationalGeographicExplorer);
    printJournal(nationalGeographicKids);
    printJournalsForPublisher(ngs);

    deleteJournal(nationalGeographic);
    deleteJournal(nationalGeographicExplorer);
    deleteJournal(nationalGeographicKids);
    deletePublisher(ngs);
}
```

Memory Management

Example: Arbitrary Number of Journals

- One of the problems with our bidirectional implementation is that it limits the number of journals to a fixed number.
- Accommodating an arbitrary number of journals requires being able to resize the *journals* array in the Publisher struct.
- We do this by dynamically allocating the *journals* array, and reallocating it if more elements are required. We did something similar earlier with the char array used as a string.



Memory Management

Example: Arbitrary Number of Journals

- Here is the new definition of Publisher:

```
/** Struct that defines a Journal */
typedef struct {        // "anonymous struct"
    char name[100];              // name of publisher
    Journal **journals;          // array of journal pointers
    unsigned int nJournals;      // number of journals
    unsigned int maxJournals;    // maximum number of journals
} Publisher;            // only known by its typedef name
```

- The *journals* field now point to an array of Journal pointers that will be allocated dynamically.
- The *maxJournals* field keeps track of the array capacity. If the array is full, it must be resized before adding another journal.

Memory Management

Example: Arbitrary Number of Journals

- Here is how the Publisher is initialized.

```
/**
 * Create and initialize a publisher.
 * @param name the publisher name
 * @return the publisher
 */
Publisher *newPublisher(const char *name) {
    Publisher *publisher = malloc(sizeof(Publisher));
    strcpy(publisher->name, name);
    publisher->nJournals = 0;          // no journals
    publisher->maxJournals = 2;        // initially, two slots available
    publisher->journals = malloc(publisher->maxJournals * sizeof(Journal*));
    return publisher;
}
```

Memory Management

Example: Arbitrary Number of Journals

- Here is how the Publisher is deleted.

```
/**
 * Delete the publisher.
 * @param publisher the publisher to delete
 */
void deletePublisher(Publisher *publisher) {
    free(publisher->journals);  // first free dynamic array
    free(publisher);
}
```

Memory Management

Arbitrary Number of Journals

- Here is how a Journal is added to a Publisher.

```
/**
 * Add a journal to a publisher.
 * @param publisher the publisher
 * @param journal the journal to add
 */
void addJournalToPublisher(Publisher *publisher, Journal *journal) {
    if (publisher->nJournals >= publisher->maxJournals) {  // out of space
        publisher->maxJournals *= 2;       // double available size
        publisher->journals =              // grow storage to new available size
            realloc(publisher->journals, publisher->maxJournals * sizeof(Journal*));
    }
    publisher->journals[publisher->nJournals++] = journal;
}
```

Memory Management

Example: Arbitrary Number of Journals

```
/** Test dynamic allocation of publisher and journal */
int main(void) {
    Publisher *ngs = newPublisher("National Geographic Society");

    Journal *nationalGeographic =
        newJournal("National Geographic", 0x00279358, ngs);
    Journal *nationalGeographicExplorer =
        newJournal("National Geographic Explorer", 0x15413357, ngs);
    Journal *nationalGeographicKids =
        newJournal("National Geographic Kids", 0x15423042, ngs);
```

Memory Management

Example: Arbitrary Number of Journals

```
    printJournal(nationalGeographic);
    printJournal(nationalGeographicExplorer);
    printJournal(nationalGeographicKids);
    printJournalsForPublisher(ngs);

    deleteJournal(nationalGeographic);
    deleteJournal(nationalGeographicExplorer);
    deleteJournal(nationalGeographicKids);
    deletePublisher(ngs);
}
```