Week 8

XMUT-NWEN 241 - 2024 T2

Systems Programming

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Content

- Introduction Dynamic Memory Management
  - `calloc`
  - `free`
  - `malloc`
  - `realloc`
  - Common Problems with Dynamic Memory

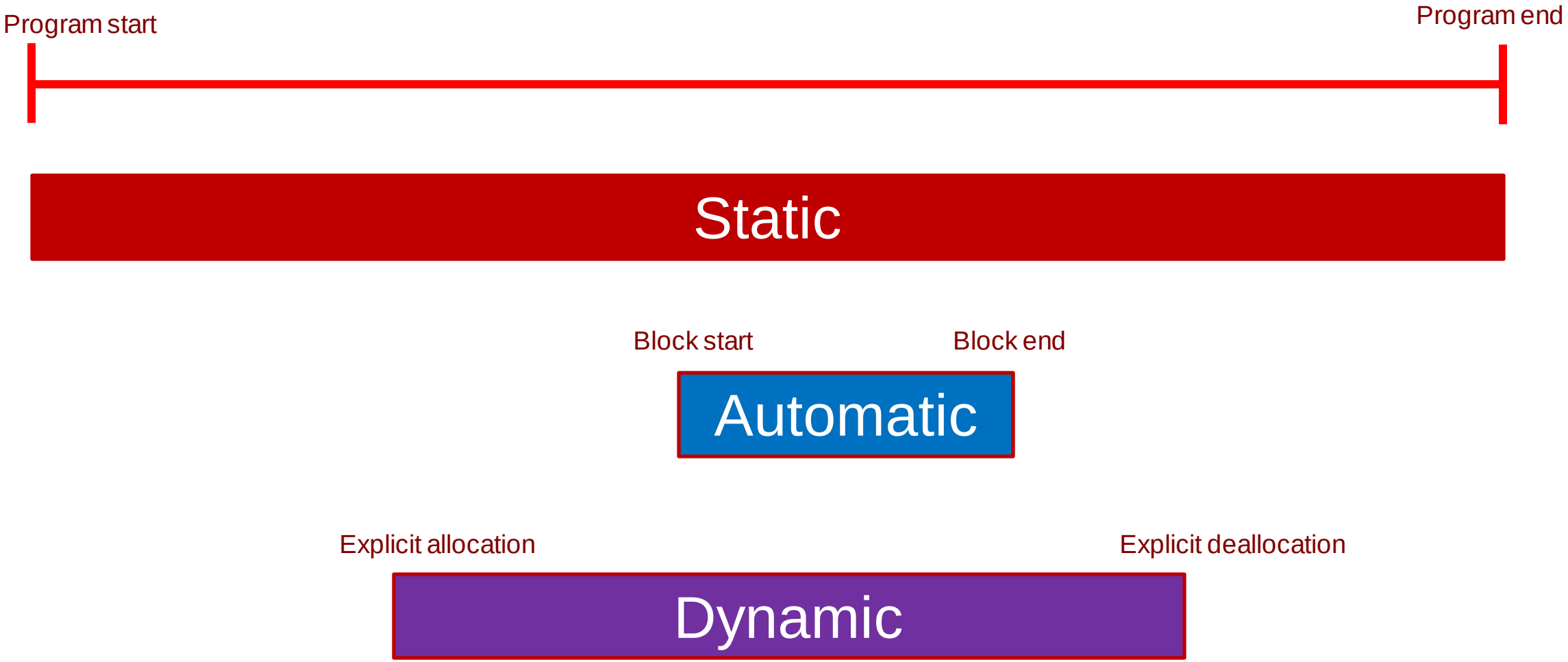
Recap: Usage of Pointers

1) Provide an alternative means of accessing information stored in arrays

2) Provide an alternative (and more efficient) means of passing parameters to functions

3) Enable dynamic data structures, that are built up from blocks of memory allocated from the heap at run time

Lifetime


Program start
Program end
Static
Block start
Block end
Automatic
Explicit allocation
Explicit deallocation
Dynamic

Why Allocate Memory Dynamically?

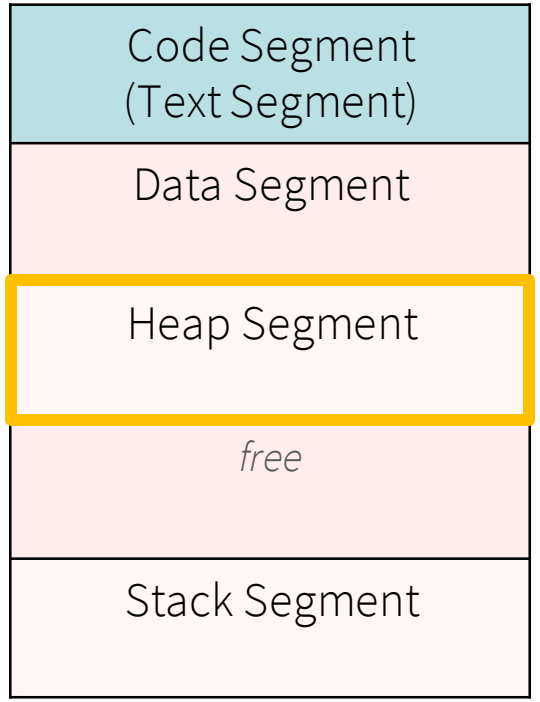
- **It may not be possible to know ahead of time the space needed by a variable (e.g., array) for storing data**

- With static allocation:
  - If predefined size is small, it may not be enough space to hold data, resulting in **program failure**
  - If predefined size is big, most of the space will not be used causing **waste or inefficiency**

Dynamic Memory Allocation

- **Allow the program to dynamically allocate memory for some variables (e.g. arrays) during the program execution**

- Approach:
  - Program has routines allowing user to request some amount of memory,
  - the user then uses this memory, and
  - returns it when they are done.
  - Memory is allocated in the *Heap Segment*



Dynamic Memory Management Functions

- `calloc` - allocate *array* of memory
- `malloc` - allocate *a single block* of memory
- `realloc` – extend or reduce the amount of space allocated previously
- `free` - free up a piece of memory that is no longer needed

Memory allocated dynamically does not go away at the end of functions, you **MUST** explicitly **free** it up

`calloc` – Allocate Memory for Array

- Function prototype:

```
void *calloc(size_t num, size_t esize)
```

  - `size_t` – special type used to indicate sizes, unsigned int
  - **`num`** – number of elements to be allocated in the array
  - **`esize`** – size (in bytes) of a single element to be allocated
    - to get the correct value, use **`sizeof(<type>)`**
    - memory of size **`num*esize`** is allocated
- `calloc` returns the address of the 1st byte of this memory
  - Cast the returned address to the appropriate type
- If not enough memory is available, `calloc` returns `NULL`

calloc Example

```
float *nums;
int a_size;
int idx;

printf("Read how many numbers:");
scanf("%d",&a_size);
nums = (float *)calloc(a_size, sizeof(float));

/* nums is now an array of floats of size a_size */
for (idx = 0; idx < a_size; idx++) {
  printf("Please enter number %d: ",idx+1);
  scanf("%f", nums+idx); /* read in the floats */
}

/* Calculate average, etc. */
```

What is a potential problem of this code?

calloc Example

Always check the return value of `calloc`, `malloc` or `realloc`!

```
float *nums;
int a_size;
int idx;

printf("Read how many numbers:");
scanf("%d",&a_size);
nums = (float *) calloc(a_size, sizeof(float));

if(nums == NULL) {
      /* exit or do some other stuff */
}
...
```

`free` – Return Memory to Heap

- Function prototype:

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

- Memory at location pointed by `ptr` is released (so that it could be used again)
- Program keeps track of each piece of memory allocated by where that memory starts
- If we free a piece of memory allocated with `calloc`, the entire array is freed (released)
- **Undefined behaviour** if we pass as address to free an address of something that was not allocated dynamically (or has already been freed)

free Example

```
float *nums;
int a_size;

printf("Read how many numbers:");
scanf("%d",&a_size);
nums = (float *) calloc(a_size, sizeof(float));

/* Use array nums */
…

/* When done with nums: */
free(nums);

/* Would be an error to do it again - free(nums) */
```

`malloc` – Allocate Memory

- Function prototype:

```
void *malloc(size_t esize)
```

- Similar to `calloc`, except we use it to allocate a single block of the given size `esize`
- `NULL` returned if not enough memory available
- Memory must be released using free if no longer needed
- Following are equivalent:

```
malloc(a_size*sizeof(float))
```

```
calloc(a_size, sizeof(float))
```

malloc Example

```
float *nums;
int a_size;
int idx;

printf("Read how many numbers:");
scanf("%d",&a_size);
nums = (float *) malloc(a_size * sizeof(float));

if(nums == NULL) {
     /* exit or do some other stuff */
}
...
```

realloc – increase/decrease memory allocation

- Function prototype:

```
void *realloc(void *ptr, size_t esize)
```

- `ptr` is a pointer to a piece of memory previously dynamically allocated
- `esize` is new size to allocate
- `NULL` returned if reallocation fails
- Function performs following action:
  1) allocates memory of size `esize`,
  2) copies the contents of the memory at `ptr` to the first part of the new piece of memory, and lastly,
  3) old block of memory is freed up
  4) Address to new piece of memory is returned

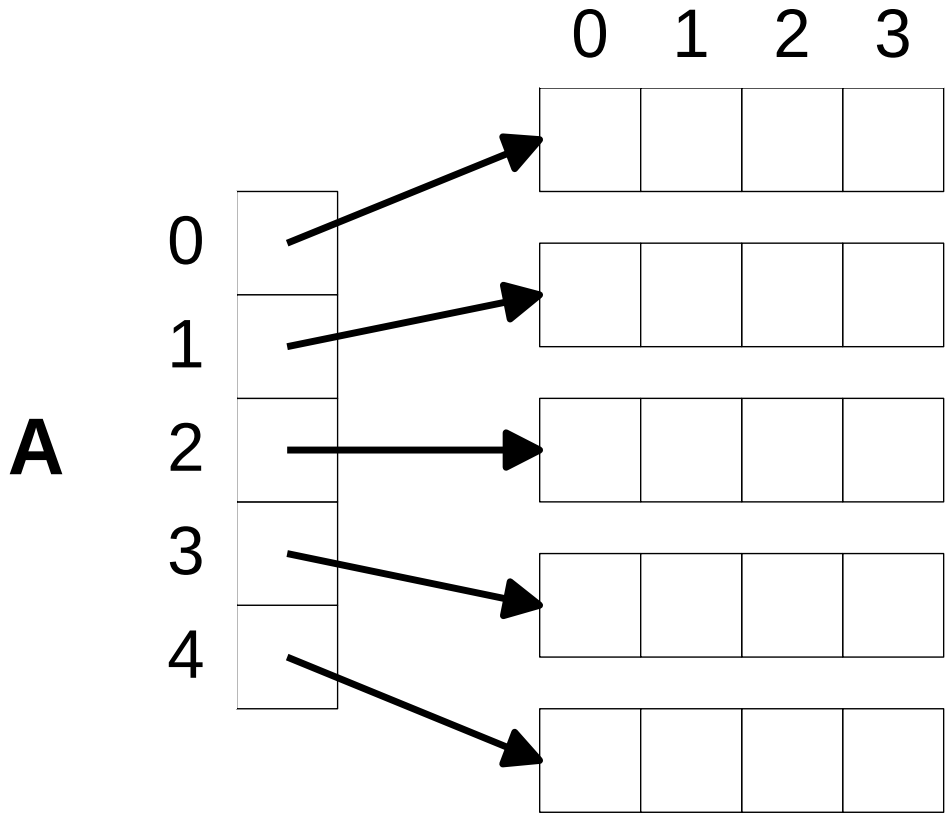
realloc Example

```
float *nums;
int a_size;

nums = (float *)calloc(5, sizeof(float));
/* nums is an array of 5 floating point values */

for (a_size = 0; a_size < 5; a_size++)
  nums[a_size] = 2.0 * a_size;
/* nums[0]=0.0, nums[1]=2.0, nums[2]=4.0, etc. */

nums = (float *)realloc(nums, 10*sizeof(float));
/* An array of 10 floating point values is allocated, the
first 5 floats from the old nums are copied as the first 5
floats of the new nums, then the old nums is released */
```

Allocating Memory for 2D array

- Can not simply allocate 2D (or higher) array dynamically

- Solution:
  1) Allocate an array of pointers (1st dimension),
  2) Make each pointer point to a 1D array of the appropriate size

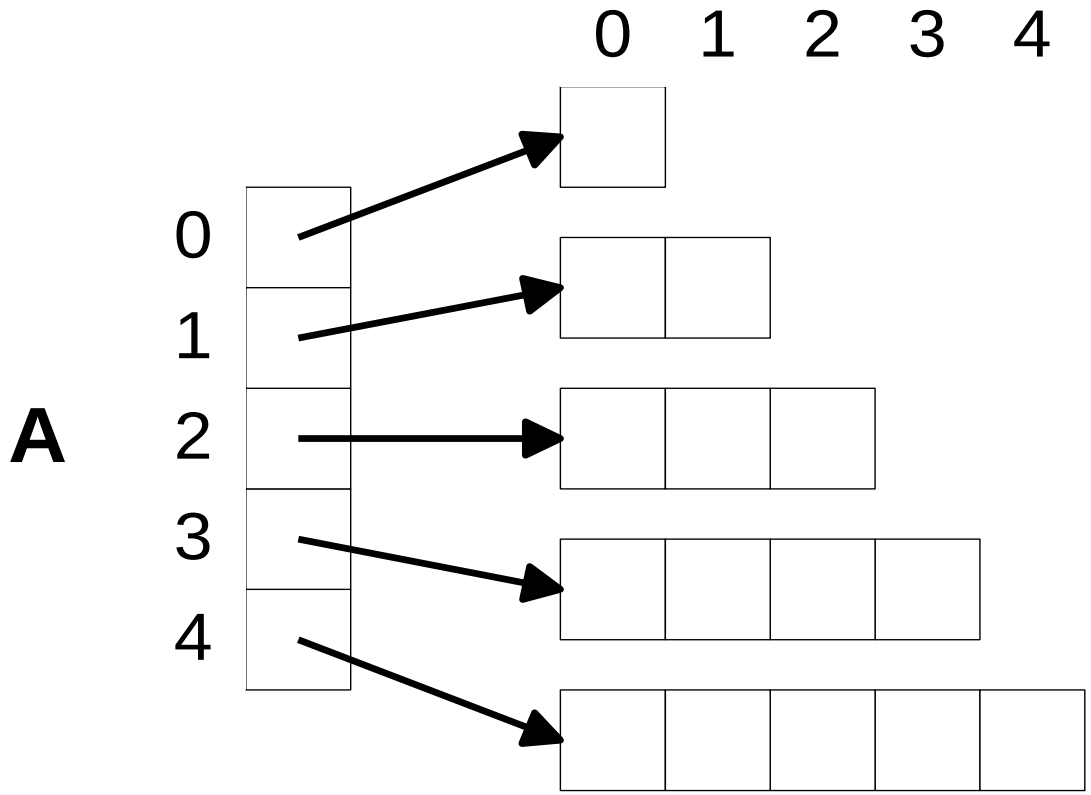


Allocating Memory for 2D array

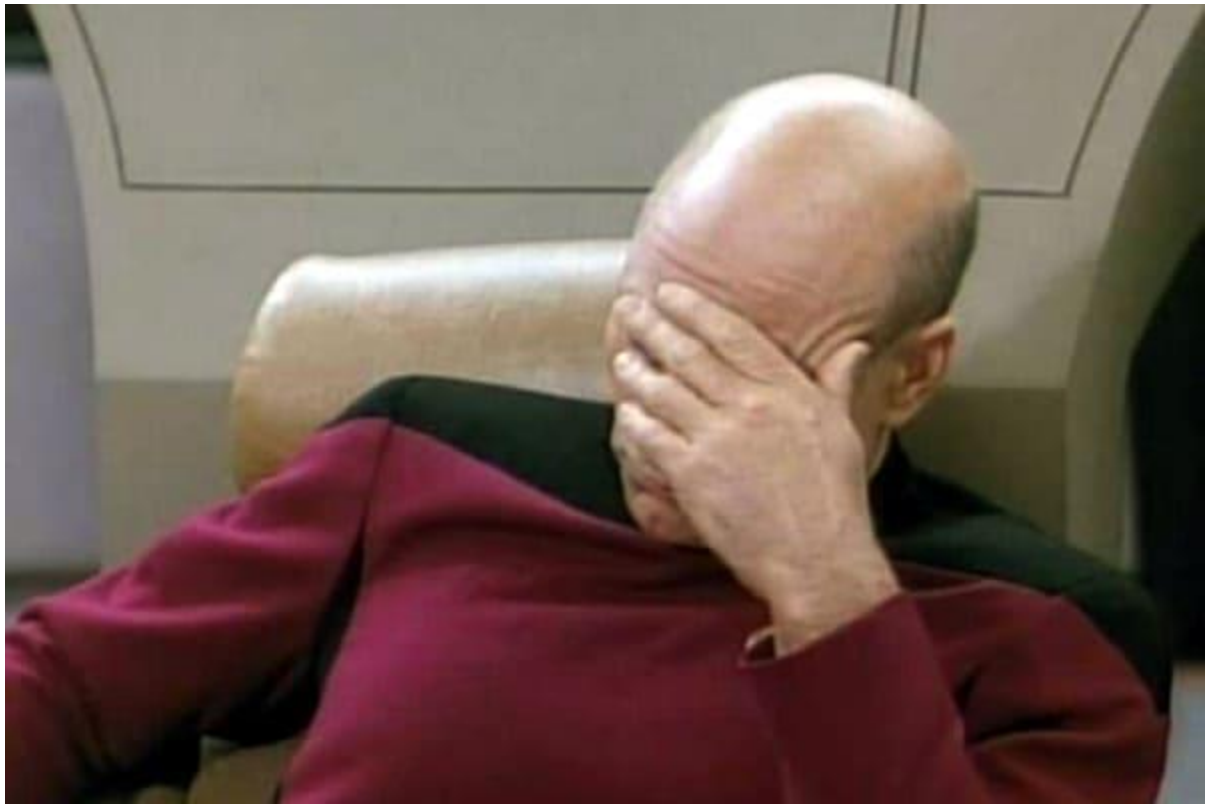
```
float **A;  /* A is an array (pointer) of float pointers */
int X;

A = (float **) calloc(5, sizeof(float *));
/* A is a 1D array (size 5) of float pointers */

for (X = 0; X < 5; X++)
{
  A[X] = (float *) calloc(4, sizeof(float));
  /* Each element of array points to an array of 4 float
     variables */
}

/* A[X][Y] is the Yth entry in the array that the Xth member of A
points to */
```

Irregular-sized 2D array

```
float **A;
int X;

A = (float **)calloc(5,
sizeof(float *));

for (X = 0; X < 5; X++){
  A[X] = (float *)
         calloc(X+1,
         sizeof(float));
}
```



Common Issues With Dynamic Memory



Issue #1

- Returning a pointer to an automatic variable

```
int *foo(void)
{
      int x;

      …

      return &x;
      /* x does not exist outside the function */
      /* Returning its address will result in unknown behaviour */
}
```

Issue #2

- Heap block overrun: similar to array going out of bounds

```
void foo(void)
{
      int *x = (int *) malloc(10 * sizeof(int));

      x[10] = 10;
      /* Allocated memory is only up to x[9] */

      …

      free(x);
}
```

Issue #3

- Memory leak: loss of pointer to allocated memory

```
int *pi;

void foo(void)
{
      pi = (int*) malloc(8*sizeof(int));
      /* Leaked the old memory pointed to by pi */
      …
      free(pi); /* foo() is done with pi, so free it */
}

int main(void)
{
      pi = (int*) malloc(4*sizeof(int));
      foo();
}
```

Issue #4

- Potential memory leak
  - Loss of pointer to beginning of memory block
  - May still recover through pointer arithmetic

```
int *ip = NULL;

void foo(void)
{
     ip = (int *) malloc(2 * sizeof(int));
     …
     ip++;
     /* ip is not pointing to the start of the block anymore */

}
```

Issue #5

- Freeing non-heap or unallocated memory

```
void foo(void)
{
   int fnh = 0;
   free(&fnh); /* Freeing stack memory */
}

void bar(void)
{
   int *fum = (int *) malloc(4 * sizeof(int));
   free(fum+1); /* fum+1 points to middle of block */
   free(fum);
   free(fum); /* Freeing already freed memory */
}
```

Detecting Memory Leaks and Other Issues

- Valgrind is an open-source tool for detecting memory management and threading bugs
- For more information: http://valgrind.org/