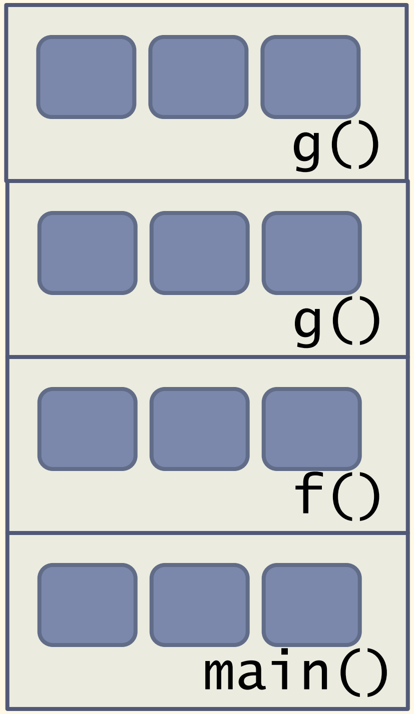
Dynamic memory allocation in C

(Reek, Ch. 11)

Overview of memory management

- Stack-allocated memory
  - When a function is called, memory is allocated for all of its parameters and local variables.
  - Each active function call has memory on the stack (with the current function call on top)
  - When a function call terminates,
    the memory is deallocated ("freed up")



- Ex: `main()` calls `f()`,
  `f()` calls `g()`
  `g()` recursively calls `g()`

Overview of memory management

- Heap-allocated memory
  - This is used for *persistent* data, that must survive beyond the lifetime of a function call
    - global variables
    - dynamically allocated memory – C statements can create new heap data (similar to new in Java/C++)
  - Heap memory is allocated in a more complex way than stack memory
  - Like stack-allocated memory, the underlying system determines where to get more memory – the programmer doesn’t have to search for free memory space!

Note: `void *` denotes a generic pointer type

Allocating new heap memory

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

- Allocate a block of `size` bytes,
  return a pointer to the block
  (`NULL` if unable to allocate block)

```
void *calloc(size_t num_elements, size_t element_size);
```

- Allocate a block of `num_elements * element_size` bytes,
  initialize every byte to zero,
  return pointer to the block
  (`NULL` if unable to allocate block)

Allocating new heap memory

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

- Given a previously allocated block starting at `ptr`,
  - change the block size to `new_size`,
  - return pointer to resized block
    - If block size is increased, contents of old block may be copied to a completely different region
    - In this case, the pointer returned will be different from the `ptr` argument, and `ptr` will no longer point to a valid memory region
- If `ptr` is `NULL`, `realloc` is identical to `malloc`

- Note: may need to cast return value of `malloc/calloc/realloc`:

```
char *p = (char *) malloc(BUFFER_SIZE);
```

Deallocating heap memory

```
void free(void *pointer);
```

- Given a pointer to previously allocated memory,
  - put the region back in the heap of unallocated memory

- Note: easy to forget to free memory when no longer needed...
  - especially if you’re used to a language with “garbage collection” like Java
  - This is the source of the notorious “memory leak” problem
  - Difficult to trace – the program will run fine for some time, until suddenly there is no more memory!

Checking for successful allocation

- Call to `malloc` might fail to allocate memory, if there's not enough available
- Easy to forget this check, annoying to have to do it every time `malloc` is called...
- Reek's solution:

```
#define malloc    DON'T CALL malloc DIRECTLY!
#define MALLOC(num,type) (type *)alloc((num)*sizeof(type))
extern void *alloc(size_t size);
```

Garbage inserted into source code if programmer uses `malloc`

Use MALLOC instead...
Scales memory region appropriately
(Note use of parameters in `#define`)
Also, calls "safe" `alloc` function

Checking for successful allocation

- implementation of `alloc`:

```
#undef malloc

void *alloc(size_t size) {
  void *new_mem;
  new_mem = malloc(size);
  if (new_mem == NULL) exit(1);
  return new_mem;
}
```

- Nice solution – as long as “terminate the program” is always the right response

Memory errors

- Using memory that you have not initialized
- Using memory that you do not own
- Using more memory than you have allocated
- Using faulty heap memory management

Using memory that you have not initialized

- Uninitialized memory read
- Uninitialized memory copy
  - not necessarily critical – unless a memory read follows

```
void foo(int *pi) {
  int j;
  *pi = j;
  /* UMC: j is uninitialized, copied into *pi */
}
void bar() {
  int i=10;
  foo(&i);
  printf("i = %d\n", i);
  /* UMR: Using i, which is now junk value */
}
```

Using memory that you don't own

- Null pointer read/write
- Zero page read/write

```
typedef struct node {
  struct node* next;
  int val;
} Node;

int findLastNodeValue(Node* head) {
  while (head->next != NULL) { /* Expect NPR */
      head = head->next;
  }
  return head->val; /* Expect ZPR */
}
```

What if head is NULL?

Using memory that you don’t own

- Invalid pointer read/write
  - Pointer to memory that hasn’t been allocated to program

```
void genIPR() {
  int *ipr = (int *) malloc(4 * sizeof(int));
  int i, j;
  i = *(ipr - 1000); j = *(ipr + 1000); /* Expect IPR */
  free(ipr);
}

void genIPW() {
  int *ipw = (int *) malloc(5 * sizeof(int));
  *(ipw - 1000) = 0; *(ipw + 1000) = 0; /* Expect IPW */
  free(ipw);
}
```

Using memory that you don't own

- Common error in 64-bit applications:
  - `int`s are 4 bytes but pointers are 8 bytes
  - If prototype of `malloc()` not provided, return value will be cast to a 4-byte `int`

Four bytes will be lopped off this value – resulting in an invalid pointer value

```
/*Forgot to #include <malloc.h>, <stdlib.h>
  in a 64-bit application*/
void illegalPointer() {
  int *pi = (int*) malloc(4 * sizeof(int));
  pi[0] = 10; /* Expect IPW */
  printf("Array value = %d\n", pi[0]); /* Expect IPR */
}
```

Using memory that you don't own

- Free memory read/write
  - Access of memory that has been freed earlier

```
int* init_array(int *ptr, int new_size) {
  ptr = (int*) realloc(ptr, new_size*sizeof(int));
  memset(ptr, 0, new_size*sizeof(int));
  return ptr;
}
int* fill_fibonacci(int *fib, int size) {
  int i;
  /* oops, forgot: fib = */ init_array(fib, size);
  /* fib[0] = 0; */ fib[1] = 1;
  for (i=2; i<size; i++)
      fib[i] = fib[i-1] + fib[i-2];
  return fib;
}
```

Remember: `realloc` may move entire block

What if array is moved to new location?

Using memory that you don't own

- Beyond stack read/write

```
char *append(const char* s1, const char *s2) {
  const int MAXSIZE = 128;
  char result[128];
  int i=0, j=0;
  for (j=0; i<MAXSIZE-1 && j<strlen(s1); i++,j++) {
      result[i] = s1[j];
  }
  for (j=0; i<MAXSIZE-1 && j<strlen(s2); i++,j++) {
      result[i] = s2[j];
  }
  result[++i] = '\0';
  return result;
}
```

`result` is a local array name – stack memory allocated

Function returns pointer to stack memory – won't be valid after function returns

Using memory that you haven’t allocated

- Array bound read/write

```
void genABRandABW() {
  const char *name = “Safety Critical";
  char *str = (char*) malloc(10);
  strncpy(str, name, 10);
  str[11] = '\0'; /* Expect ABW */
  printf("%s\n", str); /* Expect ABR */
}
```

Faulty heap management

- Memory leak

```
int *pi;
void foo() {
  pi = (int*) malloc(8*sizeof(int));
  /* Allocate memory for pi */
  /* Oops, leaked the old memory pointed to by pi */
  …
  free(pi); /* foo() is done with pi, so free it */
}
void main() {
  pi = (int*) malloc(4*sizeof(int));
  /* Expect MLK: foo leaks it */
  foo();
}
```

Faulty heap management

- Potential memory leak
  - no pointer to the beginning of a block
  - not necessarily critical – block beginning may still be reachable via pointer arithmetic

```
int *plk = NULL;
void genPLK() {
  plk = (int *) malloc(2 * sizeof(int));
   /* Expect PLK as pointer variable is incremented
       past beginning of block */
  plk++;
}
```

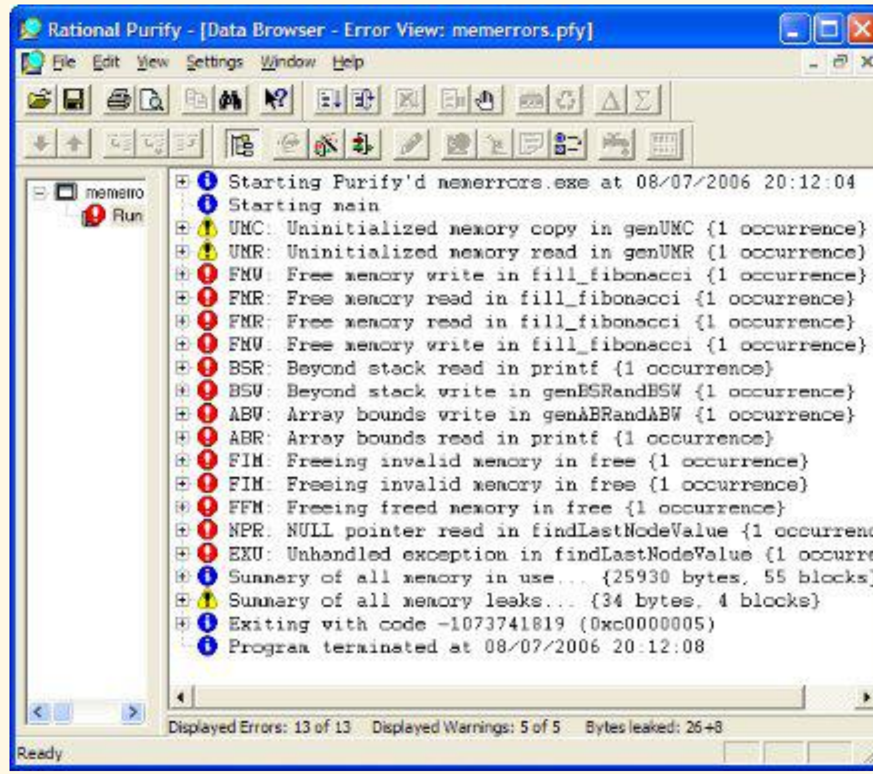
Faulty heap management

- Freeing non-heap memory
- Freeing unallocated memory

```
void genFNH() {
  int fnh = 0;
  free(&fnh); /* Expect FNH: freeing stack memory */
}
void genFUM() {
  int *fum = (int *) malloc(4 * sizeof(int));
  free(fum+1); /* Expect FUM: fum+1 points to middle
  of a block */
  free(fum);
  free(fum); /* Expect FUM: freeing already freed
  memory */
}
```

Tools for analyzing memory management

- Purify: runtime analysis for finding memory errors
  - dynamic analysis tool: collects information on memory management while program runs
  - contrast with static analysis tool like `lint`, which analyzes source code without compiling, executing it



Reference

- S.C. Gupta and S. Sreenivasamurthy. “Navigating ‘C’ in a ‘leaky’ boat? Try Purify”. http://www.ibm.com/developerworks/rational/library/06/0822_satish-giridhar/