CS 61C: Great Ideas in Computer Architecture (Machine Structures)
Dynamic Memory Management

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Agenda

- C Memory Management
- Administrivia
- Technology Break
- Common Memory Problems

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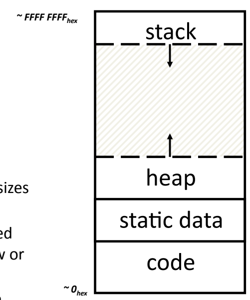
Recap: C Memory Management

- Program's *address space* contains 4 regions:
  - stack: local variables, grows downward
  - heap: space requested for pointers via `malloc()`; resizes dynamically, grows upward
  - static data: variables declared outside main, does not grow or shrink
  - code: loaded when program starts, does not change



OS prevents accesses between stack and heap (via virtual memory)

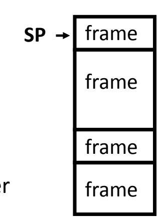
Recap: Where are Variables Allocated?

- If declared outside a procedure, allocated in "static" storage
- If declared inside procedure, allocated on the "stack" and freed when procedure returns
  - main() is treated like a procedure

```
int myGlobal;
main() {
   int myTemp;
}
```


Recap: The Stack

- Stack frame includes:
  - Return "instruction" address
  - Parameters
  - Space for other local variables
- Stack frames contiguous blocks of memory; stack pointer indicates top of stack frame
- When procedure ends, stack frame is tossed off the stack; frees memory for future stack frames



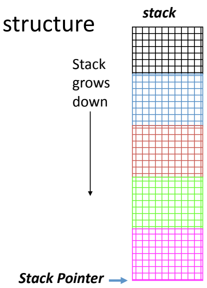
Observations

- Code, Static storage are easy: they never grow or shrink
- Stack space is relatively easy: stack frames are created and destroyed in last-in, first-out (LIFO) order
- *Managing the heap is tricky*: memory can be allocated / deallocated at any time

Recap: The Stack

- Last In, First Out (LIFO) data structure

```
main ()
{ a(0);
}
  void a (int m)
  { b(1);
  }
   void b (int n)
   { c(2);
   }
    void c (int o)
    { d(3);
    }void d (int p)
     {
     }
```



Peer Instruction: What's Wrong with this Code?

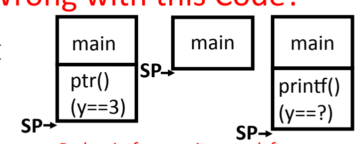
```
int *ptr () {
 int y;
 y = 3;
 return &y;
};

main () {
 int *stackAddr,content;
 stackAddr = ptr();
 content = *stackAddr;
 printf("%d", content); /* 3 */
 content = *stackAddr;
 printf("%d", content); /*13451514 */
};
```

Green: printf modifies stackAddr
Yellow: printf bug modifies content
Red: printf overwrites stack frame

Peer Instruction: What's Wrong with this Code?

```
int *ptr () {
 int y;
 y = 3;
 return &y;
};
```



Red: printf overwrites stack frame

```
main () {
 int *stackAddr,content;
 stackAddr = ptr();
 content = *stackAddr;
 printf("%d", content); /* 3 */
 content = *stackAddr;
 printf("%d", content); /*13451514 */
};
```

Never return pointers to local variable from functions
Your compiler will warn you about this – don't ignore such warnings!

Managing the Heap

- C supports five functions for heap management: **`malloc()`**, `calloc()`, **`free()`**, `cfree()`, `realloc()`
- `malloc(n)`:
  - Allocate a block of uninitialized memory
  - NOTE: Subsequent calls need not yield blocks in continuous sequence
  - `n` is an integer, indicating size of allocated memory block in bytes
  - `sizeof` determines size of given type in bytes, produces more portable code
  - Returns a pointer to that memory location; NULL return indicates no more memory
  - Think of ptr as a *handle* that also describes the allocated block of memory; Additional control information stored in the heap around the allocated block!
- Example:

```
int *ip;
ip = malloc(sizeof(int));

struct treeNode *tp;
tp = malloc(sizeof(struct tnode));
```


Managing the Heap

- `free(p)`:
  - Releases memory allocated by `malloc()`
  - `p` is pointer containing the address *originally* returned by `malloc()`

```
int *ip;
ip = malloc(sizeof(int));
... .. ..
free(ip);   /* Can you free(ip) after ip++ ? */

struct treeNode *tp;
tp = malloc(sizeof(struct treeNode));
  ... .. ..
free(tp);
```

  - When insufficient free memory, `malloc()` returns `NULL` pointer; **Check for it!**

```
if ((ip = malloc(sizeof(int))) == NULL){
    printf("\nMemory is FULL\n");
    exit(1);
}
```

  - When you free memory, you must be sure that you pass the **original address** returned from `malloc()` to `free()`; Otherwise, system exception!

Managing the Heap

- `calloc(n, size)`:
  - Allocate n elements of same data type; n can be an integer variable, use `calloc()` to allocate a dynamically size array
  - `n` is the # of array elements to be allocated
  - `size` is the number of bytes of each element
  - `calloc()` guarantees that the memory contents are initialized to zero

  E.g.: allocate an array of 10 elements

  ```
  int *ip;
  ip = calloc(10, sizeof(int));
  ```

  `*(ip+1)` refers to the 2nd element, like `ip[1]`

  `*(ip+i)` refers to the i+1th element, like `ip[i]`

  Beware of referencing beyond the allocated block: e.g., `*(ip+10)`
  - `calloc()` returns `NULL` if no further memory is available
- `cfree(p)`:
  - `cfree()` releases the memory allocated by `calloc()`; E.g.: `cfree(ip);`

Managing the Heap

- `realloc(p,size)`:
  - Resize a previously allocated block at `p` to a new `size`
  - If `p` is `NULL`, then `realloc` behaves like `malloc`
  - If `size` is 0, then `realloc` behaves like `free`, deallocating the block from the heap
  - Returns new address of the memory block; NOTE: it is likely to have moved!

  E.g.: allocate an array of 10 elements, expand to 20 elements later

  ```
  int *ip;
  ip = malloc(10*sizeof(int));
  /* always check for ip == NULL */
  … … …
  ip = realloc(ip,20*sizeof(int));
  /* always check for ip == NULL */
  /* contents of first 10 elements retained */
  … … …
  realloc(ip,0); /* identical to free(ip) */
  ```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- Technology Break
- Example

Administrivia

- Project 4: Single Cycle Processor in Logisim
  - Due Sat 27 Nov (fine to submit early!)
  - Face-to-Face grading in Lab, Th 2 Dec
- EC: Performance Improvements to Proj #3 (due Tu 29 Nov)
- Final Review Sessions:
  - Mon 6 Dec, 1400-1700, 10 Evans
- Final: Mon 13 Dec 0800-1100 (220 Hearst Gym)
  - Like midterm: T/F, M/C, short answers
  - Whole Course: readings, lectures, projects, labs, hw
  - Emphasize 2nd half of 61C + midterm mistakes

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Common Memory Problems

- Using uninitialized values
- Using memory that you don't own
  - Deallocated stack or heap variable
  - Out of bounds reference to stack or heap array
  - Using NULL or garbage data as a pointer
- Improper use of free/realloc by messing with the pointer handle returned by malloc/calloc
- Memory leaks (you allocated something you forgot to later free)

Debugging Tools

- Runtime analysis tools 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 or executing it
  - No tool is guaranteed to find ALL memory bugs – this is a very challenging programming language research problem
- *You will be introduced in Valgrind in Lab #6!*

http://valgrind.org

Using Uninitialized Values

- What is wrong with this code?

```
void foo(int *pi) {
    int j;
    *pi = j;
}

void bar() {
    int i=10;
    foo(&i);
    printf("i = %d\n", i);
}
```


Using Uninitialized Values

- What is wrong with this code?

```
void foo(int *pi) {
    int j;
    *pi = j;
    /* j is uninitialized, copied into *pi */
}

void bar() {
    int i=10;
    foo(&i);
    printf("i = %d\n", i);
    /* Using i, which now has junk value */
 }
```


Valgrind Output (Highly Abridged!)

==98863== Memcheck, a memory error detector
==98863== Using Valgrind-3.6.0 and LibVEX; rerun with -h for copyright info

==98863== Conditional jump or move depends on uninitialised value(s)
==98863==   at 0x100031A1E: __vfprintf (in /usr/lib/libSystem.B.dylib)
==98863==   by 0x100073BCA: vfprintf_l (in /usr/lib/libSystem.B.dylib)
==98863==   by 0x1000A11A6: printf (in /usr/lib/libSystem.B.dylib)
==98863==   by 0x100000EEE: main (slide21.c:13)
==98863== **Uninitialised value was created by a stack allocation**
==98863==   **at 0x100000EB0: foo (slide21.c:3)**
==98863==

Valgrind Output (Highly Abridged!)

==98863== HEAP SUMMARY:
==98863==   in use at exit: 4,184 bytes in 2 blocks
==98863==   total heap usage: 2 allocs, 0 frees, 4,184 bytes allocated
==98863==
==98863== LEAK SUMMARY:
==98863==   definitely lost: 0 bytes in 0 blocks
==98863==   indirectly lost: 0 bytes in 0 blocks
==98863==   possibly lost: 0 bytes in 0 blocks
==98863==   still reachable: 4,184 bytes in 2 blocks
==98863==   suppressed: 0 bytes in 0 blocks
==98863== Reachable blocks (those to which a pointer was found) are not shown.
==98863== To see them, rerun with: --leak-check=full --show-reachable=yes

Using Memory You Don't Own

- What is wrong with this code?

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

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


Using Memory You Don't Own

- Following a NULL pointer to mem addr 0!

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

int findLastNodeValue(Node* head) {
    while (head->next != NULL) {
    /* What if head happens to be NULL? */
        head = head->next;
    }
    return head->val; /* What if head is NULL? */
}
```


Using Memory You Don't Own

- What is wrong with this code?

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

void WriteMem() {
    *ipw = malloc(5 * sizeof(int));
    *(ipw - 1000) = 0; *(ipw + 1000) = 0;
    free(ipw);
}
```


Using Memory You Don't Own

- Using pointers beyond the range that had been malloc'd
  - May look obvious, but what if mem refs had been result of pointer arithmetic that erroneously took them out of the allocated range?

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

void WriteMem() {
    *ipw = malloc(5 * sizeof(int));
    *(ipw - 1000) = 0; *(ipw + 1000) = 0;
    free(ipw);
}
```


Using Memory You Don't Own

- What is wrong with this code?

```
int* init_array(int *ptr, int new_size) {
   ptr = realloc(ptr, new_size*sizeof(int));
   memset(ptr, 0, new_size*sizeof(int));
   return ptr;
}

int* fill_fibonacci(int *fib, int size) {
   int i;
   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;
}
```


Using Memory You Don't Own

- Improper matched usage of mem handles

```
int* init_array(int *ptr, int new_size) {
   ptr = 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 You Don't Own

- What's wrong with this code?

```
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;
}
```


Using Memory 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 You Haven't Allocated

- What is wrong with this code?

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


Using Memory You Haven't Allocated

- Reference beyond array bounds

```
void StringManipulate() {
   const char *name = “Safety Critical";
   char *str = malloc(10);
   strncpy(str, name, 10);
   str[10] = '\0';
   /* Write Beyond Array Bounds */
   printf("%s\n", str);
   /* Read Beyond Array Bounds */
}
```


Faulty Heap Management

- What is wrong with this code?

```
int *pi;
void foo() {
   pi = malloc(8*sizeof(int));
   …
   free(pi);
}

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


Faulty Heap Management

- Memory leak: *more mallocs than frees*

```
int *pi;
void foo() {
   pi = 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 = malloc(4*sizeof(int));
   foo(); /* Memory leak: foo leaks it */
}
```

Faulty Heap Management

- What is wrong with this code?

```
int *plk = NULL;
void genPLK() {
  plk = malloc(2 * sizeof(int));
  … … …
  plk++;
}
```


Faulty Heap Management

- Potential memory leak – handle has been changed, do you still have copy of it that can correctly be used in a later free?

```
int *plk = NULL;
void genPLK() {
  plk = malloc(2 * sizeof(int));
  … … …
  plk++; /* Potential leak: pointer variable
  incremented past beginning of block! */
}
```


Faulty Heap Management

- What is wrong with this code?

```
void FreeMemX() {
  int fnh = 0;
  free(&fnh);
}

void FreeMemY() {
  int *fum = malloc(4 * sizeof(int));
  free(fum+1);
  free(fum);
  free(fum);
}
```


Faulty Heap Management

- Can't free non-heap memory; Can't free memory that hasn't been allocated

```
void FreeMemX() {
  int fnh = 0;
  free(&fnh); /* Oops! freeing stack memory */
}

void FreeMemY() {
  int *fum = malloc(4 * sizeof(int));
  free(fum+1);
  /* fum+1 is not a proper handle; points to middle
  of a block */
  free(fum);
  free(fum);
  /* Oops! Attempt to free already freed memory */
}
```


Summary

- C has three pools of data memory (+ code memory)
  – Static storage: global variable storage, basically permanent, entire program run
  – The Stack: local variable storage, parameters, return address
  – *The Heap (dynamic storage): `malloc()`/`calloc()` grabs space from here, `free()`/`cfree()` returns it, `realloc()` resizes space*
- Common (Dynamic) Memory Problems
  – Using uninitialized values
  – Accessing memory beyond your allocated region
  – Improper use of free/realloc by messing with the pointer handle returned by malloc/calloc
  – Memory leaks: mismatched malloc/free pairs