EECS 22: Advanced C Programming

Lecture 9

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Lecture 9: Overview

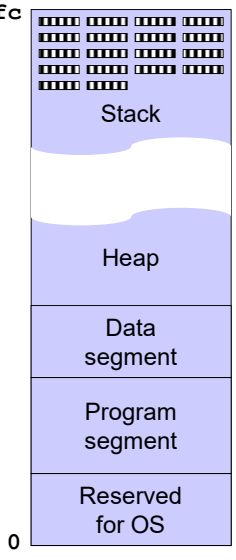
- Review Variable Lifetimes
- Memory Organization
  - Memory segmentation
  - Memory errors
- Storage Classes
  - Program example **`StorageClasses.c`**
- Recursion Revisited
  - Program example **`Fibonacci.c`**
  - Program example **`Fibonacci2.c`**

Variable Lifetimes

- Lifetime of Variables
  - Global variables (storage class **`static`**, **`extern`**)
    - From program start to end
  - Local variables (storage class **`register`**, **`auto`**)
    - From beginning of execution of their compound statement
      - Stack frame entry
    - To leaving their compound statement
      - Stack frame exit
  - Function parameters (storage class **`register`**, **`auto`**)
    - From beginning of function call
    - To returning from the function call
  - Dynamically allocated objects (more details in Lecture 16)
    - From successful return of **`malloc()`**
    - To call of **`free()`**

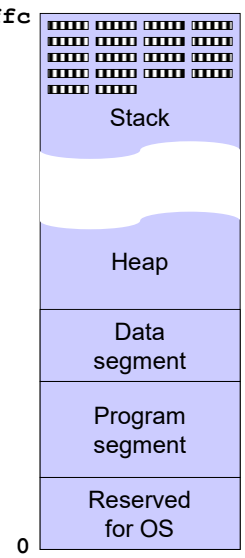
Memory Organization

- Memory Segmentation
  - typical (virtual) memory layout on processor with 4-byte words and 4 GB of memory
  - Stack
    - grows and shrinks dynamically (from top)
    - contains function call hierarchy
    - stores stack frames with local variables
  - Heap
    - "free" storage
    - dynamic allocation by the program
  - Data segment
    - global (and **`static`**) variables
  - Program segment (aka. text segment)
    - program instructions (binary code)
  - Reserved area for operating system



Memory Organization

- Memory Segmentation
  - typical (virtual) memory layout on processor with 4-byte words and 4 GB of memory
- Memory errors
  - *Out of memory*
    - Stack and heap collide
  - *Segmentation fault*
    - access outside allocated segments
    - e.g. access to segment reserved for OS
  - *Bus error*
    - mis-aligned word access
    - e.g. word access to an address that is not divisible by 4



Storage Classes

- C Language distinguishes 2 Storage Classes
  - (but uses 5 keywords and a default, depending on scope)
  - Automatic (i.e. on the stack)
    - `auto` local variable, on stack (default)
    - `register` local variable, in register (preferred) or on stack
  - Static (i.e. in the data segment)
    - `static` static variable in data segment
    - `extern` declaration of global variable in data segment
  - At compile-time, a 3rd "storage class" exists
    - `typedef` definition of an alias for a type at compile time (no storage)

Storage Classes

Keyword	Global Scope	Local Scope
(none)	Global variable in data segment	Local variable on stack
auto	n/a	Local variable on stack
register	n/a	Local variable on stack or in register (preferred)
static	Global variable in data segment (int. linkage)	Local variable in data segment
extern	Declaration of global variable in data segment (ext. linkage)	Declaration of global variable in data segment (ext. linkage)
typedef	Alias for a type at compile time (no storage in memory)	Alias for a type at compile time (no storage in memory)

Storage Classes vs. Linkage

- ANSI C language uses the keywords **extern** and **static** not only for the specification of storage classes, but also for specification of *linkage* of functions and variables
  - Unfortunate re-use of keywords easily causes confusion!
- Linkage
  - External Linkage: **extern**
    - The object is accessible across multiple translation units
    - Example:
```
extern double sqrt(double x);
extern const double pi;
```
  - Internal Linkage: **static**
    - The object is accessible in its own translation unit only
    - Example:
```
static double my_sqrt(double x);
static const double my_pi = 3.1415927;
```
- We will introduce programs with multiple translation units in detail in the following lectures

Storage Classes

- Program example: **`StorageClasses.c`** (part 1/3)

```
/* StorageClasses.c: example for storage classes and linkage */
/* author: Rainer Doemer                                      */
/*                                                            */
/* modifications:                                             */
/* 10/13/13 RD  initial version                               */

/*** global scope ***/

       void f(int); /* global function (defined below) */
extern void g(int); /* global function (defined somewhere else)*/
static void h(int); /* internal function (defined below) */

        double x;   /* global variable (defined here) */
extern  double y;   /* global variable (defined somewhere else)*/
static  double z;   /* internal global variable (defined here) */

typedef double t;   /* type definition */

...
```


Storage Classes

- Program example: **`StorageClasses.c`** (part 2/3)

```
...
void f(int p)
{
    /*** local scope ***/

            int i; /* local variable (on stack) */
    auto    int j; /* local variable (on stack) */
    register int r; /* local variable, preferably in register */
    static   int n = 0; /* static local variable */

    n++; /* count executions of this function */
    for(i=0; i<n; i++)
    { for(j=0; j<p; j++)
      { g(i*j);
      }
    }
    for(r=0; r<1000000; r++)
    { h(r);
    }
}
...
```

Storage Classes

- Program example: **`StorageClasses.c`** (part 3/3)

```
...

static void h(int p)
{
    g(p + (x*y*z));
}

/* EOF */
```


Recursion Revisited

- Example: Fibonacci series
  - Mathematical properties:
    - The first two numbers are 0 and 1
    - Every subsequent number is the sum of the previous two
  - Recursive definition:
    - Base case: $fibonacci(0) = 0,\ fibonacci(1) = 1$
    - Recursion step: $fibonacci(n) = fibonacci(n-1) + fibonacci(n-2)$

Recursion Revisited

- Program example: **`Fibonacci.c`** (part 1/2)

```
/* Fibonacci.c: example demonstrating recursion */
/* author: Rainer Doemer                        */
/* modifications:                               */
/* 11/14/04 RD  initial version                 */

#include <stdio.h>

/* function definition */

long fibonacci(long n)
{
   if (n <= 1)  /* base case */
      { return n;
       } /* fi */
   else         /* recursion step */
      { return fibonacci(n-1) + fibonacci(n-2);
       } /* esle */
} /* end of fibonacci */

/* main function */
...
```


Recursion Revisited

- Program example: **`Fibonacci.c`** (part 2/2)

```
...
int main(void)
{
   /* variable definitions */
   long int n, f;

   /* input section */
   printf("Please enter value n: ");
   scanf("%ld", &n);

   /* computation section */
   f = fibonacci(n);

   /* output section */
   printf("The %ld-th Fibonacci number is %ld.\n", n, f);

   /* exit */
   return 0;
} /* end of main */

/* EOF */
```

Recursion Revisited

- Timed example session: **`Fibonacci.c`**

```
% /usr/bin/time -f "%U seconds" ./Fibonacci
Please enter value n: 41
The 41-th Fibonacci number is 165580141.
2.37 seconds
% /usr/bin/time -f "%U seconds" ./Fibonacci
Please enter value n: 42
The 42-th Fibonacci number is 267914296.
3.71 seconds
% /usr/bin/time -f "%U seconds" ./Fibonacci
Please enter value n: 43
The 43-th Fibonacci number is 433494437.
5.62 seconds
% /usr/bin/time -f "%U seconds" ./Fibonacci
Please enter value n: 44
The 44-th Fibonacci number is 701408733.
8.97 seconds
% /usr/bin/time -f "%U seconds" ./Fibonacci
Please enter value n: 45
The 45-th Fibonacci number is 1134903170.
14.26 seconds
%
```


Recursion Revisited

- Example Revisited: Fibonacci series
  - Recursive definition:
    - Base case: $fibonacci(0) = 0,\ fibonacci(1) = 1$
    - Recursion step: $fibonacci(n) = fibonacci(n-1) + fibonacci(n-2)$
  - Mathematical properties:
    - The first two numbers are 0 and 1
    - Every subsequent number is the sum of the previous two
  - ➢ Problem:
    - Program run-time grows exponentially! (factor 1.6, golden ratio)
  - ➢ Idea:
    - If we *remember the previously calculated numbers*, we can calculate the next number immediately!
    - ➢ Whenever a new number is calculated, keep it stored in a **`static`** array in memory
    - ➢ When a number is present in the memory, just look it up

Recursion Revisited

- Program example: **`Fibonacci2.c`** (part 1/3)

```
/* Fibonacci2.c: example demonstrating recursion */
/* author: Rainer Doemer                         */
/* modifications:                                */
/* 11/09/11 RD  version with 'static' memory     */
/* 11/14/04 RD  initial version                  */

#include <stdio.h>

#define MEM_SIZE 100

/* function definition */

...
```


Recursion Revisited

- Program example: **`Fibonacci2.c`** (part 2/3)

```
long fibonacci(long n)
{  static long fib[MEM_SIZE] = {0,1}; /* memory */
   if (n <= 1)          /* base case */
      { return n;
       } /* fi */
   else                 /* previouly calculated results */
      { if (n < MEM_SIZE && fib[n])
          { return fib[n];
           } /* fi */
        else            /* recursion step */
          { long f;
            f = fibonacci(n-1) + fibonacci(n-2);
            if (n < MEM_SIZE)
               { fib[n] = f;   /* remember this */
                 } /* fi */
            return f;
           } /* esle */
       } /* esle */
} /* end of fibonacci */
...
```

Recursion Revisited

- Program example: **`Fibonacci2.c`** (part 3/3)

```
...
int main(void)
{
   /* variable definitions */
   long int n, f;

   /* input section */
   printf("Please enter value n: ");
   scanf("%ld", &n);

   /* computation section */
   f = fibonacci(n);

   /* output section */
   printf("The %ld-th Fibonacci number is %ld.\n", n, f);

   /* exit */
   return 0;
} /* end of main */

/* EOF */
```


Recursion Revisited

- Timed example session: **`Fibonacci2.c`**

```
% /usr/bin/time -f "%U seconds" ./Fibonacci2
Please enter value n: 41
The 41-th Fibonacci number is 165580141.
0.00 seconds
% /usr/bin/time -f "%U seconds" ./Fibonacci2
Please enter value n: 42
The 42-th Fibonacci number is 267914296.
0.00 seconds
% /usr/bin/time -f "%U seconds" ./Fibonacci2
Please enter value n: 43
The 43-th Fibonacci number is 433494437.
0.00 seconds
% /usr/bin/time -f "%U seconds" ./Fibonacci2
Please enter value n: 44
The 44-th Fibonacci number is 701408733.
0.00 seconds
% /usr/bin/time -f "%U seconds" ./Fibonacci2
Please enter value n: 45
The 45-th Fibonacci number is 1134903170.
0.00 seconds
%
```