EECS 22: Advanced C Programming

Lecture 13 (TuTh)

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Part 1: Overview

- Dynamic Memory Allocation
  - Dynamic Memory Errors
  - Validating Dynamic Memory Usage
  - **`valgrind`**

Dynamic Memory Allocation

- Typical Dynamic Memory Usage Errors
  - Omitting **malloc()**: Access to unallocated memory
  - Reading uninitialized memory
  - Omitting **free()**: Memory *leak*
  - Freeing memory too early, or multiple times
  - …
- Validating Dynamic Memory Usage
  - **valgrind**: A memory error detector (and more)
    - Instruments the program at (right before) run-time
    - Intercepts and checks calls to **malloc()** and **free()**
    - Intercepts and checks memory accesses
    - Reports any errors to the user (or a log file)
  - ➢ Use **valgrind** for testing and debugging!
    - There should be 0 errors and 0 bytes leaked!

Dynamic Memory Allocation

- Example Student Records: **Student.h**

```
/* Student.h: header file for student records */

#ifndef STUDENT_H
#define STUDENT_H

#define SLEN 40

struct Student
{  int  ID;
   char Name[SLEN+1];
   char Grade;
};
typedef struct Student STUDENT;

/* allocate a new student record */
STUDENT *NewStudent(int ID, char *Name, char Grade);

/* delete a student record */
void DeleteStudent(STUDENT *s);

/* print a student record */
void PrintStudent(STUDENT *s);

#endif /* STUDENT_H */
```

Dynamic Memory Allocation

- Example Student Records: **Student.c** (part 1/3)

```
/* Student.c: maintaining student records */

#include "Student.h"
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include <assert.h>

/* allocate a new student record */
STUDENT *NewStudent(int ID, char *Name, char Grade)
{   STUDENT *s;
    s = malloc(sizeof(STUDENT));
    if (! s)
       { perror("Out of memory! Aborting...");
         exit(10);
       } /* fi */
    s->ID = ID;
    strncpy(s->Name, Name, SLEN);
    s->Name[SLEN] = '\0';
    s->Grade = Grade;
    return s;
} /* end of NewStudent */
...
```

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Dynamic Memory Allocation

- Example Student Records: **Student.c** (part 2/3)

```
...

/* delete a student record */
void DeleteStudent(STUDENT *s)
{
    assert(s);
    free(s);
} /* end of DeleteStudent */

/* print a student record */
void PrintStudent(STUDENT *s)
{
    assert(s);
    printf("Student ID:    %d\n", s->ID);
    printf("Student Name:  %s\n", s->Name);
    printf("Student Grade: %c\n", s->Grade);
} /* end of PrintStudent */

...
```

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Dynamic Memory Allocation

- Example Student Records: **`Student.c`** (part 3/3)

```
...
/* test the student record functions */
int main(void)
{   STUDENT *s1 = NULL, *s2 = NULL;
    printf("Creating 2 student records...\n");
    s1 = NewStudent(1001, "Jane Doe", 'A');
    s2 = NewStudent(1002, "John Doe", 'C');

    printf("Printing the student records...\n");
    PrintStudent(s1);
    PrintStudent(s2);

    printf("Deleting the student records...\n");
    DeleteStudent(s1);
    s1 = NULL;
    DeleteStudent(s2);
    s2 = NULL;

    printf("Done.\n");
    return 0;
} /* end of main */

/* EOF */
```


Dynamic Memory Allocation

- Example Student Records: **`Makefile`**

```
# Makefile: Student Records

# macro definitions
CC = gcc
DEBUG = -g
#DEBUG = -O2
CFLAGS = -Wall -ansi –std=c99 $(DEBUG) -c
LFLAGS = -Wall $(DEBUG)

# dummy targets
all: Student

clean:
        rm -f *.o
        rm -f Student

# compilation rules
Student.o: Student.c Student.h
        $(CC) $(CFLAGS) Student.c -o Student.o

Student: Student.o
        $(CC) $(LFLAGS) Student.o -o Student

# EOF
```

Dynamic Memory Allocation

- Example Session

```
% vi Student.h
% vi Student.c
% vi Makefile
% make
gcc -Wall -ansi –std=c99 -g -c Student.c -o Student.o
gcc -Wall -g Student.o -o Student
% ./Student
Creating 2 student records...
Printing the student records...
Student ID:    1001
Student Name:  Jane Doe
Student Grade: A
Student ID:    1002
Student Name:  John Doe
Student Grade: C
Deleting the student records...
Done.
%
```

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Dynamic Memory Allocation

- Example Session

```
% valgrind ./Student
==23638== Memcheck, a memory error detector
==23638== […]
==23638== Command: Student
Creating 2 student records...
Printing the student records...
Student ID:    1001
Student Name:  Jane Doe
Student Grade: A
Student ID:    1002
Student Name:  John Doe
Student Grade: C
Deleting the student records...
Done.
==23638== HEAP SUMMARY:
==23638==    in use at exit: 0 bytes in 0 blocks
==23638==   total heap usage: 2 allocs, 2 frees, 96 bytes allocated
==23638==
==23638== All heap blocks were freed -- no leaks are possible
==23638== ERROR SUMMARY: 0 errors from 0 contexts […]
%
```

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Part 2: Overview

- Pointer Operations
  - Definition, initialization and assignment
  - Pointer dereferencing
  - Pointer arithmetic
    - Increment, decrement
  - Pointer comparison
- Pointers and Arrays
  - Equivalence!
  - Array layout in linear address space

Pointer Operations

- *Pointers* are variables whose values are *addresses*
  - The *"address-of"* operator (**&**) returns a pointer!
- Pointer Definition
  - The unary ***** operator indicates a pointer type in a definition

```
int x = 42;    /* regular integer variable */
int *p;        /* pointer to an integer */
```

- Pointer initialization or assignment
  - A pointer may be set to the address of another variable

```
p = &x;        /* p points to x */
```

  - A pointer may be set to **0** (points to no object)

```
p = 0;         /* p points to no object */
```

  - A pointer may be set to **NULL** (points to "NULL" object)

```
#include <stdio.h>   /* defines NULL as 0 */
p = NULL;      /* p points to no object */
```

Pointer Operations

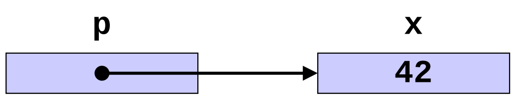
- Pointer Dereferencing
  - The unary ***** operator dereferences a pointer to the value it points to (“*content-of*” operator)

```
#include <stdio.h>

int  x = 42;   /* regular integer variable */
int *p = NULL; /* pointer to an integer */

p = &x;        /* make p point to x */
printf(“x is %d, content of p is %d\n”, x, *p);
```

```
x is 42, content of p is 42
```



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Pointer Operations

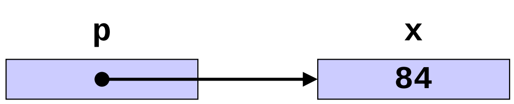
- Pointer Dereferencing
  - The unary ***** operator dereferences a pointer to the value it points to (“*content-of*” operator)

```
#include <stdio.h>

int  x = 42;   /* regular integer variable */
int *p = NULL; /* pointer to an integer */

p = &x;        /* make p point to x */
printf(“x is %d, content of p is %d\n”, x, *p);
*p = 2 * *p;   /* multiply content of p by 2 */
printf(“x is %d, content of p is %d\n”, x, *p);
```

```
x is 42, content of p is 42
x is 84, content of p is 84
```



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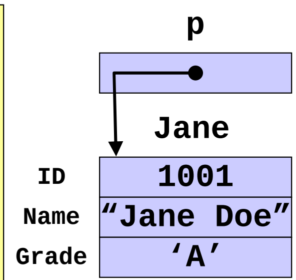
Pointer Operations

- Pointer Dereferencing
  - The **->** operator dereferences a pointer to a structure to the named structure member (*"member-access"* operator)

```
struct Student
{  int  ID;
   char Name[40];
   char Grade;
};
struct Student Jane =
{1001, "Jane Doe", 'A'};
struct Student *p = &Jane;
void PrintStudent(void)
{
   printf("ID:    %d\n", p->ID);
   printf("Name:  %s\n", p->Name);
   printf("Grade: %c\n", p->Grade);
}
```




```
ID:    1001
Name:  Jane Doe
Grade: A
```

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Pointer Operations

- Pointer Arithmetic
  - Pointers pointing into arrays may be ...
    - ... incremented to point to the next array element
    - ... decremented to point to the previous array element
      - ➢ Boundaries apply! Pointing outside of **A[0]** to **A[N]** is undefined!

```
int x[5] = {10,20,30,40,50}; /* array of 5 integers */
int *p;                      /* pointer to integer */
p = &x[1];                   /* point p to x[1] */
printf("%d, ", *p);          /* print content of p */
```

```
20,
```

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Pointer Operations

- Pointer Arithmetic
  - Pointers pointing into arrays may be ...
    - ... incremented to point to the next array element
    - ... decremented to point to the previous array element
      - ➢ Boundaries apply! Pointing outside of **A[0]** to **A[N]** is undefined!

```
int x[5] = {10,20,30,40,50}; /* array of 5 integers */
int *p;                      /* pointer to integer */

p = &x[1];                   /* point p to x[1] */
printf("%d, ", *p);          /* print content of p */
p++;                         /* increment p by 1 */
printf("%d, ", *p);          /* print content of p */
```

```
20, 30,
```

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Pointer Operations

- Pointer Arithmetic
  - Pointers pointing into arrays may be ...
    - ... incremented to point to the next array element
    - ... decremented to point to the previous array element
      - ➢ Boundaries apply! Pointing outside of **A[0]** to **A[N]** is undefined!

```
int x[5] = {10,20,30,40,50}; /* array of 5 integers */
int *p;                      /* pointer to integer */

p = &x[1];                   /* point p to x[1] */
printf("%d, ", *p);          /* print content of p */
p++;                         /* increment p by 1 */
printf("%d, ", *p);          /* print content of p */
p--;                         /* decrement p by 1 */
printf("%d, ", *p);          /* print content of p */
```

```
20, 30, 20,
```

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Pointer Operations

- Pointer Arithmetic
  - Pointers pointing into arrays may be ...
    - ... incremented to point to the next array element
    - ... decremented to point to the previous array element
      - ➢ Boundaries apply! Pointing outside of **A[0]** to **A[N]** is undefined!

```
int x[5] = {10,20,30,40,50}; /* array of 5 integers */
int *p;                      /* pointer to integer */

p = &x[1];                   /* point p to x[1] */
printf("%d, ", *p);          /* print content of p */
p++;                         /* increment p by 1 */
printf("%d, ", *p);          /* print content of p */
p--;                         /* decrement p by 1 */
printf("%d, ", *p);          /* print content of p */
p += 2;                      /* increment p by 2 */
printf("%d, ", *p);          /* print content of p */
```

```
20, 30, 20, 40,
```


Pointer Operations

- Pointer Comparison
  - Pointers may be compared for object identification or position
    - operators **==** and **!=** are useful to determine *object identity*
    - operators **<**, **<=**, **>=**, and **>** are applicable *only* to objects in the *same array*

```
int x[5] = {10,20,10,20,10}; /* array of 5 integers */
int *p1, *p2;                /* pointers to integer */

p1 = &x[1]; p2 = &x[3];      /* point to x[1], x[3] */

if (p1 == p2)
  { printf("p1 and p2 are identical!\n");
   }
if (*p1 == *p2)
  { printf("Contents of p1 and p2 are the same!\n");
   }
```

```
Contents of p1 and p2 are the same!
```

Pointer Operations

- Pointer Comparison
  - Pointers may be compared for object identification or position
    - operators **==** and **!=** are useful to determine object *identity*
    - operators **<**, **<=**, **>=**, and **>** are applicable *only* to objects in the *same array*

```
int x[5] = {10,20,10,20,10}; /* array of 5 integers */
int *p1, *p2;                /* pointers to integer */
p1 = &x[1]; p2 = &x[3];      /* point to x[1], x[3] */
p1 += 2;                     /* increment p1 by 2 */
if (p1 == p2)
  { printf("p1 and p2 are identical!\n");
  }
if (*p1 == *p2)
  { printf("Contents of p1 and p2 are the same!\n");
  }
```

```
p1 and p2 are identical!
Contents of p1 and p2 are the same!
```

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Pointer Operations

- Pointer Comparison
  - Pointers may be compared for object identification or position
    - operators **==** and **!=** are useful to determine object *identity*
    - operators **<**, **<=**, **>=**, and **>** are applicable *only* to objects in the *same array*

```
int x[5] = {10,20,10,20,10}; /* array of 5 integers */
int *p1, *p2;                /* pointers to integer */
p1 = &x[1]; p2 = &x[3];      /* point to x[1], x[3] */

if (p1 > p2)
  { printf("p1 points to an element after p2!\n");
  }
if (p1 < p2)
  { printf("p1 points to an element before p2!\n");
  }
```

```
p1 points to an element before p2!
```

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Pointers and Arrays

- In C, *Pointers and Arrays are equivalent!*
  - A pointer represents an address in memory
  - An array is represented by the address of its first element in memory
- Passing Arrays and Pointers to Functions
  - Arrays are passed *by reference*
  - Pointers *are references* and passed as such
- Array Access is equivalent to Pointer Dereferencing
  - Example:

```
int A[10];
...
A[0] = 42;
...
A[5] = 17;
```

```
int A[10], *p = &A[0];
...
*p = 42;
...
*(p+5) = 17;
```

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Pointers and Arrays

- Dynamic Arrays
  - Example 1:
    Fixed 1-dim. array
    - Fixed definition
    - Passed as fixed array
    - Fixed array access
    - ➢ Fixed size everywhere!

```
int Sum(int A[100])
{
  int i, sum = 0;
  for(i=0; i<100; i++)
  { sum += A[i];
  }
  return sum;
}

int main(void)
{
  int d[100], s;
  ...
  s = Sum(d);
  ...
  return 0;
}
```

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Pointers and Arrays

- Dynamic Arrays
  - Example 2: Fixed 1-dim. array
    - Fixed definition
    - Passed as fixed array plus size
    - ➢ Received as pointer and size!
    - ➢ Accessed via pointer with offset!

```
int Sum(int *p, int m)
{
  int i, sum = 0;
  for(i=0; i<m; i++)
  { sum += *(p + i);
  }
  return sum;
}

int main(void)
{
  int d[100], s;
  ...
  s = Sum(d, 100);
  ...
  return 0;
}
```

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Pointers and Arrays

- Dynamic Arrays
  - Example 3: Dynamic 1-dim. array
    - ➢ Dynamic allocation
    - ➢ Passed as pointer plus size
    - ➢ Received as pointer and size!
    - ➢ Accessed via pointer with offset!

```
int Sum(int *p, int m)
{
  int i, sum = 0;
  for(i=0; i<m; i++)
  { sum += *(p + i);
  }
  return sum;
}

int main(void)
{
  int *d, s;
  d = malloc(sizeof(int)*100);
  if (!d)
     { exit(10); }
  ...
  s = Sum(d, 100);
  free(d);
  ...
  return 0;
}
```

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Pointers and Arrays

- Dynamic Arrays
  - Example 4:
    Fixed 2-dim. array
    - Fixed definition
    - Passed as fixed array
    - Fixed array access
    - ➢ Fixed sizes everywhere!

```
int Sum(int A[5][20])
{
  int i, j, sum = 0;
  for(i=0; i<5; i++)
    for(j=0; j<20; j++)
    { sum += A[i][j];
    }
  return sum;
}

int main(void)
{
  int d[5][20], s;
  ...
  s = Sum(d);
  ...
  return 0;
}
```

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Pointers and Arrays

- Dynamic Arrays
  - Example 5:
    Mixed 2-dim. array
    - Fixed definition of dimension 1 (columns)
    - Dynamic allocation of dimension 2 (rows)
    - ➢ Passed as array with dynamic dimension 2 (number of rows) and sizes
    - ➢ Fixed array access
    - ➢ Multi-dimensional arrays are arrays of arrays…

```
int Sum(int A[][20], int m,int n)
{
  int i, j, sum = 0;
  for(i=0; i<m; i++)
    for(j=0; j<n; j++)
    { sum += A[i][j];
    }
  return sum;
}

int main(void)
{
  int (*d)[20], s;
  d = malloc(sizeof(int[20])*5);
  if (!d)
     { exit(10); }
  ...
  s = Sum(d, 5, 20);
  free(d);
  ...
  return 0;
}
```

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Pointers and Arrays

- Dynamic Arrays
  - Example 6:
    Dynamic 2-dim. array
    - Dynamic allocation of all dimensions
    - Passed as pointer
    - Received as pointer!
    - Accessed via pointer!
  - An array…
    - of any dimension
    - of any size

    …can be mapped into linear address space!

```c
int Sum(int *p, int m, int n)
{
  int i, j, sum = 0;
  for(i=0; i<m; i++)
    for(j=0; j<n; j++)
    { sum += *(p + i*n + j);
    }
  return sum;
}

int main(void)
{
  int *d, s;
  d = malloc(sizeof(int)*5*20);
  if (!d)
     { exit(10); }
  ...
  s = Sum(d, 5, 20);
  free(d);
  ...
  return 0;
}
```