

EECS 10: Computational Methods in Electrical and Computer Engineering

Review of Lectures 18 - 24

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Review of Lectures 18 - 24

- Lecture 18: Recursion
- Lecture 19: Structures, unions, enumerators
- Lecture 20: Binary data representation
- Lecture 21: Memory organization, pointers
- Lecture 22: Pointer operations, string operations
- Lecture 23: File processing
- Lecture 24: Translation units

Recursion

- Introduction
 - *Recursion* is often an alternative to *Iteration*
 - Recursion is a very simple concept, yet very powerful
 - Recursion is present in nature
 - Trees have branches, which have branches, which have branches, ... which have leaves.
 - Recursion is traversal of hierarchy
 - *Traverse* (climb) a tree to the top:
 - start at the root
 - at a leaf, stop
 - at a branch, *traverse* one branch
 - *Traverse* a file system on a computer
 - start at the current directory
 - at a file, process the file
 - at a directory, *traverse* the directory

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Recursion

- Recursive Function
 - Function that calls itself ...
 - ... directly, or
 - ... indirectly
- Concept of Recursion
 - Trivial *base case*
 - Return value defined for simple case
 - Example: `if (arg == 0) {return 1; }`
 - *Recursion step*
 - Reduce the problem towards the base case
 - Make a recursive function call
 - Example: `if (arg > 0) { return ...fct(arg-1); }`
- Termination of Recursion
 - Converging of recursive calls to the base case
 - Recursive call must be “simpler” than current call

```
int f(...)
{
  ...
  f(...);
  ...
}
```

```
int a(...)
{
  ...
  b(...);
  ...
}
int b(...)
{
  ...
  a(...);
  ...
}
```

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Recursion

- Example: Factorial function $n!$
 - The factorial of a non-negative integer is
 - $n! = n * (n-1) * (n-2) * (n-3) * \dots * 1$
 - This can be written as
 - $n! = n * ((n-1) * ((n-2) * ((n-3) * (\dots * 1))))$
 - Recursive definition:
 - $n=1: 1! = 1$ (base case)
 - $n>1: n! = n * (n-1)!$ (recursion step)
 - Example computation:

$$\begin{aligned}
 5! &= 5 * 4! \\
 &= 5 * (4 * 3!) \\
 &= 5 * (4 * (3 * 2!)) \\
 &= 5 * (4 * (3 * (2 * 1!))) \\
 &= 5 * (4 * (3 * (2 * 1))) \\
 &= 5 * (4 * (3 * 2)) \\
 &= 5 * (4 * 6) \\
 &= 5 * 24 \\
 &= 120
 \end{aligned}$$

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Recursion

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

```

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

#include <stdio.h>

/* function definition */
long factorial(long n)
{
    if (n == 1) /* base case */
    { return 1;
      } /* fi */
    else /* recursion step */
    { return n * factorial(n-1);
      } /* esle */
} /* end of factorial */

...

```

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Recursion

- Program example: `Factorial.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 = factorial(n);

    /* output section */
    printf("The factorial of %ld is %ld.\n", n, f);

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

/* EOF */
```

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Recursion

- Example session: `Factorial.c`

```
% vi Factorial.c
% gcc Factorial.c -o Factorial -Wall -ansi
% Factorial
Please enter value n: 1
The factorial of 1 is 1.
% Factorial
Please enter value n: 2
The factorial of 2 is 2.
% Factorial
Please enter value n: 3
The factorial of 3 is 6.
% Factorial
Please enter value n: 5
The factorial of 5 is 120.
% Factorial
Please enter value n: 10
The factorial of 10 is 3628800.
%
```

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Recursion vs. Iteration

- Example: Factorial function $n!$
 - The factorial of a non-negative integer is
 - $n! = n * (n-1) * (n-2) * (n-3) * \dots * 1$
 - This can be written as
 - $n! = n * ((n-1) * ((n-2) * ((n-3) * (\dots * 1))))$
 - *Recursive* definition:
 - $n=1: 1! = 1$ (base case)
 - $n>1: n! = n * (n-1)!$ (recursion step)
 - *Iterative* implementation:
 - Compute n products in a loop
 - $n! = n * (n-1) * (n-2) * (n-3) * \dots * 1$
 - `p = n;`
 - `for (f=n-1; f>=1; f--)`
 - `{ p = p * f; }`

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Recursion vs. Iteration

- Program example: `Factorial2.c` (part 1/2)

```

/* Factorial2.c: example demonstrating iteration */
/* author: Rainer Doemer */
/* modifications: */
/* 11/14/04 RD initial version (based on Factorial.c) */
#include <stdio.h>

/* function definition */
long factorial(long n)
{
    long product, factor;
    product = n;
    for(factor = n-1; factor >=1; factor--)
        { product *= factor;
          } /* rof */
    return product;
} /* end of factorial */

...

```

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Recursion vs. Iteration

- Program example: **Factorial2.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 = factorial(n);

    /* output section */
    printf("The factorial of %ld is %ld.\n", n, f);

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

/* EOF */

```

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Recursion vs. Iteration

- Example session: **Factorial2.c**

```

% cp Factorial.c Factorial2.c
% vi Factorial2.c
% gcc Factorial2.c -o Factorial2 -Wall -ansi
% Factorial2
Please enter value n: 1
The factorial of 1 is 1.
% Factorial2
Please enter value n: 2
The factorial of 2 is 2.
% Factorial2
Please enter value n: 3
The factorial of 3 is 6.
% Factorial2
Please enter value n: 5
The factorial of 5 is 120.
% Factorial2
Please enter value n: 10
The factorial of 10 is 3628800.
%

```

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Recursion

- Example 2: Fibonacci series
 - Sequence of integers
 - 0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, 233, 377, 610, 987, ...
 - Mathematical properties
 - The first two numbers are 0 and 1
 - Every subsequent Fibonacci number is the sum of the previous two Fibonacci numbers
 - Ratio of successive Fibonacci numbers is ...
 - ... converging to constant value 1.618...
 - ... called *Golden Ratio* or *Golden Mean*
 - Recursive definition:
 - Base case: $fibonacci(0) = 0$
 $fibonacci(1) = 1$
 - Recursion step: $fibonacci(n) = fibonacci(n-1) + fibonacci(n-2)$

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Recursion

- 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 */
...

```

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Recursion

- 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 */

```

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Recursion

- Example session: `Fibonacci.c`

```

% cp Factorial.c Fibonacci.c
% vi Fibonacci.c
% gcc Fibonacci.c -o Fibonacci -Wall -ansi
% Fibonacci
Please enter value n: 1
The 1-th Fibonacci number is 1.
% Fibonacci
Please enter value n: 10
The 10-th Fibonacci number is 55.
% Fibonacci
Please enter value n: 20
The 20-th Fibonacci number is 6765.
% Fibonacci
Please enter value n: 30
The 30-th Fibonacci number is 832040.
% Fibonacci
Please enter value n: 40
The 40-th Fibonacci number is 102334155.
%

```

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Data Structures

- Structures (aka. records): **struct**
 - User-defined, composite data type
 - Type is a composition of (different) sub-types
 - Fixed set of members
 - Names and types of members are fixed at structure definition
 - Member access by name
 - Member-access operator: *structure_name.member_name*
- Example:

```
struct S { int i; float f;} s1, s2;

s1.i = 42;      /* access to members */
s1.f = 3.1415;
s2 = s1;       /* assignment */
s1.i = s1.i + 2*s2.i;
```

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Data Structures

- Structure Declaration
 - Declaration of a user-defined data type
- Structure Definition
 - Definition of structure members and their type
- Structure Instantiation and Initialization
 - Definition of a variable of structure type
 - Initializer list defines initial values of members
- Example:

```
struct Student;          /* declaration */

struct Student          /* definition */
{ int ID;               /* members */
  char Name[40];
  char Grade;
};

struct Student Jane =   /* instantiation */
{1001, "Jane Doe", 'A'}; /* initialization */
```

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Data Structures

- Structure Access
 - Members are accessed by their name
 - Member-access operator .
- Example:

```

struct Student
{
  int ID;
  char Name[40];
  char Grade;
};

struct Student Jane =
{1001, "Jane Doe", 'A'};

void PrintStudent(struct Student s)
{
  printf("ID:    %d\n", s.ID);
  printf("Name:  %s\n", s.Name);
  printf("Grade: %c\n", s.Grade);
}

```

Jane	
ID	1001
Name	"Jane Doe"
Grade	'A'

```

ID:    1001
Name:  Jane Doe
Grade: A

```

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Data Structures

- Unions: **union**
 - User-defined, composite data type
 - Type is a composition of (different) sub-types
 - Fixed set of *mutually exclusive* members
 - Names and types of members are fixed at union definition
 - Member access by name
 - Member-access operator: *union_name.member_name*
 - *Only one member may be used at a time!*
 - *All members share the same location in memory!*
- Example:

```

union U { int i; float f;} u1, u2;

u1.i = 42;      /* access to members */
u2.f = 3.1415;
u1.f = u2.f;    /* destroys u1.i! */

```

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Data Structures

- Union Declaration
 - Declaration of a user-defined data type
- Union Definition
 - Definition of union members and their type
- Union Instantiation and Initialization
 - Definition of a variable of union type
 - *Single* initializer defines value of *first* member
- Example:

```
union HeightOfTriangle; /* declaration */
union HeightOfTriangle /* definition */
{ int Height; /* members */
  int LengthOfSideA;
  float AngleBeta;
};
union HeightOfTriangle H /* instantiation */
= { 42 }; /* initialization */
```

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Data Structures

- Union Access
 - Members are accessed by their name
 - Member-access operator .
- Example:

```
union HeightOfTriangle
{ int Height;
  int SideA;
  float Beta;
};
union HeightOfTriangle t1, t2, t3
= { 42 };
```

Height/	t1
SideA/	0
Beta	
Height/	t2
SideA/	0
Beta	
Height/	t3
SideA/	42
Beta	

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Data Structures

- Union Access
 - Members are accessed by their name
 - Member-access operator .
- Example:

```
union HeightOfTriangle
{ int   Height;
  int   SideA;
  float Beta;
};

union HeightOfTriangle t1, t2, t3
= { 42 };

void SetHeight(void)
{
  t1.Height = 10;
  t2.SideA = t1.Height / 2;
  t3.Beta = 90.0;
}
```

	t1
Height/	
SideA/	10
Beta	
	t2
Height/	
SideA/	5
Beta	
	t3
Height/	
SideA/	90.0
Beta	

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Data Structures

- Enumerators: `enum`
 - User-defined data type
 - Members are an enumeration of integral constants
 - Fixed set of members
 - Names and values of members are fixed at enumerator definition
 - Members are constants
 - Member values cannot be changed after definition
- Example:

```
enum E { red, yellow, green };
enum E LightNS, LightEW;

LightEW = green;          /* assignment */
if (LightNS == green)    /* comparison */
  { LightEW = red; }
```

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Data Structures

- Enumerator Declaration
 - Declaration of a user-defined data type
- Enumerator Definition
 - Definition of enumerator members and their value
- Enumerator Instantiation and Initialization
 - Definition of a variable of enumerator type
 - Initializer should be one member of the enumerator
- Example:

```
enum Weekday;           /* declaration */
enum Weekday           /* definition */
{ Monday, Tuesday,    /* members */
  Wednesday, Thursday,
  Friday, Saturday, Sunday
};

enum Weekday Today     /* instantiation */
= Wednesday;          /* initialization */
```

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Data Structures

- Enumerator Values
 - Enumerator values are integer constants
 - By default, enumerator values start at 0 and are incremented by 1 for each following member
- Example:

Today

Wednesday

Day: 2

```
enum Weekday
{ Monday,
  Tuesday,
  Wednesday,
  Thursday,
  Friday,
  Saturday,
  Sunday
};

enum Weekday Today
= Wednesday;

void PrintWeekday(
    enum Weekday d)
{
    printf("Day: %d\n", d);
}
```

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Data Structures

- Enumerator Values
 - Enumerator values are integer constants
 - By default, enumerator values start at 0 and are incremented by 1 for each following member
 - Specific enumerator values may be defined by the user
- Example:

Today

Wednesday

Day: 3

```
enum Weekday
{ Monday = 1,
  Tuesday,
  Wednesday,
  Thursday,
  Friday,
  Saturday,
  Sunday
};

enum Weekday Today
= Wednesday;

void PrintWeekday(
    enum Weekday d)
{
    printf("Day: %d\n", d);
}
```

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Data Structures

- Enumerator Values
 - Enumerator values are integer constants
 - By default, enumerator values start at 0 and are incremented by 1 for each following member
 - Specific enumerator values may be defined by the user
- Example:

Today

Wednesday

Day: 4

```
enum Weekday
{ Monday = 2,
  Tuesday,
  Wednesday,
  Thursday,
  Friday,
  Saturday,
  Sunday = 1
};

enum Weekday Today
= Wednesday;

void PrintWeekday(
    enum Weekday d)
{
    printf("Day: %d\n", d);
}
```

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Data Structures

- Type definitions: `typedef`
 - A *typedef* can be defined as an alias type for another type
 - A *typedef* definition follows the same rules as a variable definition
 - Type definitions are usually used to abbreviate access to user-defined types
- Examples:

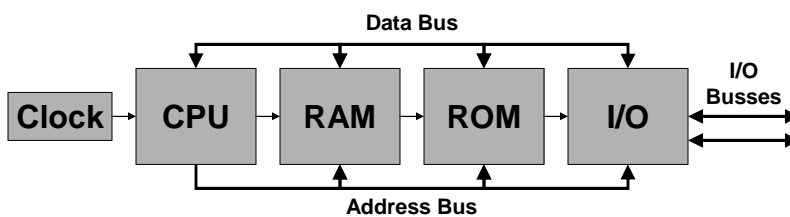
```
typedef long MyInteger;

typedef enum Weekday Day;
Day Today;

typedef struct Student Scholar;
Scholar Jane, John;
```

Basic Computer Architecture

- Essential Computer Components
 - Central Processing Unit (CPU)
 - e.g. Intel Pentium, Motorola PowerPC, Sun SPARC, ...
 - Random Access Memory (RAM)
 - storage for program and data, read and write access
 - Read Only Memory (ROM)
 - fixed storage for basic input/output system (BIOS)
 - I/O Units
 - Input/output units connecting to peripherals



Binary Data Representation

- Programs and data in a computer are represented in binary format
 - 1 *bit* (binary digit), 2 possible values
 - 0 (false, “no”, power off, “empty”, ...)
 - 1 (true, “yes”, power on, “solid”, ...)
 - 1 *byte* = 8 bits ($2^8 = 256$ values)
 - in C, type `char` equals one byte*
 - 1 *word* = 4 bytes* ($2^{32} = 4294967296$ values)
 - in C, type `int` equals one word
- Memory size is measured in Bytes
 - 1 KB = 1024 byte = 1 “kilo byte”
 - 1 MB = 1024*1024 byte = 1 “mega byte”
 - 1 GB = 1024*1024*1024 byte = 1 “giga byte”

(*architecture dependent!)

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Binary Data Representation

- Memory is composed of addressable bytes
 - Example:
1 KB of memory
 - What is the value at address 7?

7 0 1 1 0 1 0 1 0

7 6 5 4 3 2 1 0

$$= 0*2^7 + 1*2^6 + 0*2^5 + 0*2^4 + 1*2^3 + 1*2^2 + 0*2^1 + 1*2^0$$

$$= 0*128 + 1*64 + 0*32 + 0*16 + 1*8 + 1*4 + 0*2 + 1*1$$

$$= 64 + 8 + 4 + 1$$

$$= 77$$

0	0	1	1	0	1	0	1	0
1	0	1	1	0	1	0	1	0
2	0	1	1	0	1	0	1	0
3	0	1	1	0	1	0	1	0
4	0	1	1	0	1	0	1	0
5	0	1	1	0	1	0	1	0
6	0	1	1	0	1	0	1	0
7	0	1	1	0	1	0	1	0
8	0	1	1	0	1	0	1	0
9	0	1	1	0	1	0	1	0
10	0	1	1	0	1	0	1	0
11	0	1	1	0	1	0	1	0
...								
1020	0	1	1	0	1	0	1	0
1021	0	1	1	0	1	0	1	0
1022	0	1	1	0	1	0	1	0
1023	0	1	1	0	1	0	1	0

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Binary Data Representation

- Number Systems
 - DEC: Decimal numbers
 - Base 10, digits 0, 1, 2, 3, ..., 9
 - e.g. $157 = 1 \cdot 10^2 + 5 \cdot 10^1 + 7 \cdot 10^0$
 - BIN: Binary numbers
 - Base 2, digits 0, 1
 - e.g. $10011101_2 = 1 \cdot 2^7 + 0 \cdot 2^6 + \dots + 1 \cdot 2^0$
 - OCT: Octal numbers
 - Base 8, digits 0, 1, 2, 3, ..., 7
 - e.g. $235_8 = 2 \cdot 8^2 + 3 \cdot 8^1 + 5 \cdot 8^0$
 - HEX: Hexadecimal numbers
 - Base 16, digits 0, 1, 2, 3, ..., 9, A, B, C, ..., F
 - e.g. $9D_{16} = 9 \cdot 16^1 + 13 \cdot 16^0$

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Binary Data Representation

- Number Systems

DEC	BIN	OCT	HEX
0	0000	0	0
1	0001	1	1
2	0010	2	2
3	0011	3	3
4	0100	4	4
5	0101	5	5
6	0110	6	6
7	0111	7	7
8	1000	10	8
9	1001	11	9
10	1010	12	A
11	1011	13	B
12	1100	14	C
13	1101	15	D
14	1110	16	E
15	1111	17	F

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Binary Data Representation

- Number Systems (signed vs. unsigned)

SDEC	UDEC	BIN	OCT	HEX
0	0	0000	0	0
1	1	0001	1	1
2	2	0010	2	2
3	3	0011	3	3
4	4	0100	4	4
5	5	0101	5	5
6	6	0110	6	6
7	7	0111	7	7
-8	8	1000	10	8
-7	9	1001	11	9
-6	10	1010	12	A
-5	11	1011	13	B
-4	12	1100	14	C
-3	13	1101	15	D
-2	14	1110	16	E
-1	15	1111	17	F

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Binary Data Representation

- Number Systems

- Signed representation: *two's complement*

- to obtain the negative of any number in binary representation, ...

- ... invert all bits,
- ... and add 1

- Example: 4-bit two's complement

SDEC	UDEC	BIN	OCT	HEX
...
7	7	0111	7	7
-8	8	1000	10	8
-7	9	1001	11	9
...

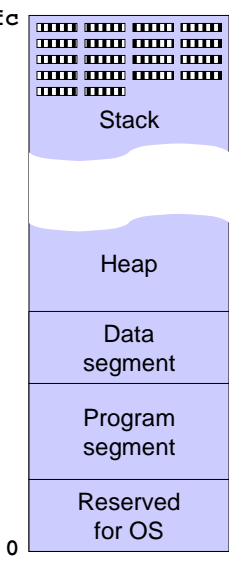
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Memory Organization

- Memory Segmentation
 - typical (virtual) memory layout on processor with 4-byte words and 1 GB of memory
 - Stack
 - grows and shrinks dynamically
 - function call hierarchy
 - stack frames with local variables
 - Heap
 - “free” storage
 - dynamic allocation by the user
 - Data segment
 - global (and static) variables
 - Program segment
 - stores binary program code
 - Reserved area for operating system



bfff fffc

Stack

Heap

Data segment

Program segment

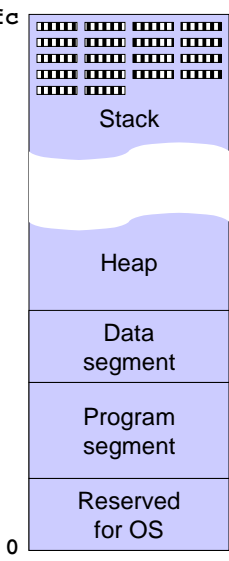
Reserved for OS

0

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Memory Organization

- Memory Segmentation
 - typical (virtual) memory layout on processor with 4-byte words and 1 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



bfff fffc

Stack

Heap

Data segment

Program segment

Reserved for OS

0

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Objects in Memory

- Data in memory is organized as a set of objects
- Every object has ...
 - ... a *type* (e.g. `int`, `double`, `char[5]`)
 - type is known to the compiler at compile time
 - ... a *value* (e.g. `42`, `3.1415`, `"text"`)
 - value is used for computation of expressions
 - ... a *size* (number of bytes in the memory)
 - in C, the `sizeof` operator returns the size of a variable or type
 - ... a *location* (address in the memory)
 - in C, the "address-of" operator (`&`) returns the address of an object
- Variables ...
 - ... serve as identifiers for objects
 - ... are bound to objects
 - ... give objects a name

Objects in Memory

- Example: Variable values, addresses, and sizes

```
int x = 42;
int y = 13;
char s[] = "Hello World!";

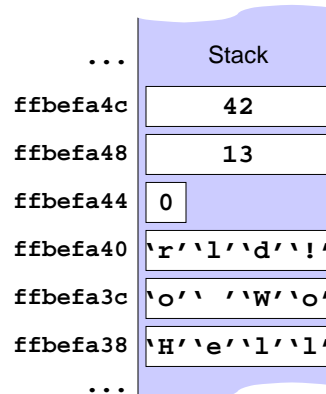
printf("Value of x is %d.\n", x);
printf("Address of x is %p.\n", &x);
printf("Size of x is %u.\n", sizeof(x));
printf("Value of y is %d.\n", y);
printf("Address of y is %p.\n", &y);
printf("Size of y is %u.\n", sizeof(y));
printf("Value of s is %s.\n", s);
printf("Address of s is %p.\n", &s);
printf("Size of s is %u.\n", sizeof(s));
printf("Value of s[1] is %c.\n", s[1]);
printf("Address of s[1] is %p.\n", &s[1]);
printf("Size of s[1] is %u.\n", sizeof(s[1]));
```

Objects in Memory

- Example: Variable values, addresses, and sizes

```
int x = 42;
int y = 13;
char s[] = "Hello World!";
...
```

```
Value of x is 42.
Address of x is ffbefa4c.
Size of x is 4.
Value of y is 13.
Address of y is ffbefa48.
Size of y is 4.
Value of s is Hello World!.
Address of s is ffbefa38.
Size of s is 13.
Value of s[1] is e.
Address of s[1] is ffbefa39.
Size of s[1] is 1.
```



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Pointers

- *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
 - A pointer may be set to 0 (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 */
```

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Pointers

- 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
0

x
42

Pointers

- 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
```



Pointers

- Pointer Dereferencing

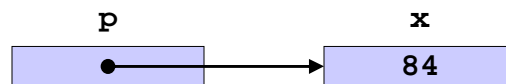
- The unary * operator dereferences a pointer to the value it points to (“content-of” operator)

```
#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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Pointers

- Pointer Dereferencing

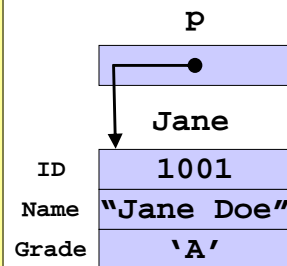
- The -> operator dereferences a pointer to a structure to the content of a structure member

```
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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Pointers

- Pointer Arithmetic

- Pointers pointing into arrays may be ...

- ... incremented to point to the next array element
- ... decremented to point to the previous array element

```
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,
```

Pointers

- Pointer Comparison

- Pointers may be compared for equality

- operators == and != are useful to determine *identity*
- operators <, <=, >=, and > are *not* applicable

```
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!
```


Pointers

- Pointer Comparison

- Pointers may be compared for equality

- operators == and != are useful to determine *identity*
- operators <, <=, >=, and > are *not* applicable

```
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!
```

Pointers

- String Operations using Pointers

- Example: String length

```
int Length(char *s)
{
    int l = 0;
    char *p = s;

    while(*p != 0)
    { p++;
      l++;
    }
    return l;
}
```

```
char s1[] = "ABC";
char s2[] = "Hello World!";

printf("Length of %s is %d\n",
       s1, Length(&s1[0]));
printf("Length of %s is %d\n",
       s2, Length(&s2[0]));
```

```
Length of ABC is 3
Length of Hello World! is 12
```

Pointers

- String Operations using Pointers

- Example: String length

```
int Length(char *s)
{
    int l = 0;
    char *p = s;

    while(*p != 0)
    {
        p++;
        l++;
    }
    return l;
}
```

```
char s1[] = "ABC";
char s2[] = "Hello World!";

printf("Length of %s is %d\n",
      s1, Length(&s1[0]));
printf("Length of %s is %d\n",
      s2, Length(s2));
```

```
Length of ABC is 3
Length of Hello World! is 12
```

- Array and pointer types are equivalent

- `s2` is an array, but can be passed as a pointer argument
- Character array `s2` is same as character pointer `&s2[0]`

Pointers

- String Operations using Pointers

- Example: String length

```
int Length(char *s)
{
    int l = 0;
    char *p = s;

    while(*p != 0)
    {
        p++;
        l++;
    }
    return l;
}
```

```
char s1[] = "ABC";
char *s2 = "Hello World!";

printf("Length of %s is %d\n",
      s1, Length(s1));
printf("Length of %s is %d\n",
      s2, Length(s2));
```

```
Length of ABC is 3
Length of Hello World! is 12
```

- Array and pointer types are equivalent

- `s1` is an array of characters, `s2` is a pointer to character
- Both `s1` and `s2` can be passed to character pointer `s`

Pointers

- String Operations using Pointers

- Example: String length

```
int Length(char s[])
{
    int l = 0;
    char *p = s;

    while(*p != 0)
    {
        p++;
        l++;
    }
    return l;
}
```

```
char s1[] = "ABC";
char *s2 = "Hello World!";

printf("Length of %s is %d\n",
      s1, Length(s1));
printf("Length of %s is %d\n",
      s2, Length(s2));
```

```
Length of ABC is 3
Length of Hello World! is 12
```

- Array and pointer types are equivalent

- `s1` is an array of characters, `s2` is a pointer to character
- Both `s1` and `s2` can be passed to character array `s`

Pointers

- String Operations using Pointers

- Example: String copy

```
void Copy(
    char *Dst,
    char *Src)
{
    do{
        *Dst = *Src;
        Dst++;
    } while(*Src++);
}
```

```
char s1[] = "ABC";
char s2[] = "Hello World!";

printf("s1 is %s, s2 is %s\n",
      s1, s2);
Copy(s2, s1);
printf("s1 is %s, s2 is %s\n",
      s1, s2);
```

```
s1 is ABC, s2 is Hello World!
s1 is ABC, s2 is ABC
```

- Passing pointers as arguments to functions

- Function can modify caller data by pointer dereferencing
- **Passing pointers = Pass by reference!**

Pointers

- String Operations using Pointers

- Example: String copy

```
void Copy(
    char *Dst,
    const char *Src)
{
    do{
        *Dst = *Src;
        Dst++;
    } while(*Src++);
}
```

```
char s1[] = "ABC";
char s2[] = "Hello World!";

printf("s1 is %s, s2 is %s\n",
      s1, s2);
Copy(s2, s1);
printf("s1 is %s, s2 is %s\n",
      s1, s2);
```

```
s1 is ABC, s2 is Hello World!
s1 is ABC, s2 is ABC
```

- Passing pointers as arguments to functions

- Function can modify caller data by pointer dereferencing
- Type qualifier **const**:
Modification by pointer dereferencing *not* allowed!

Pointers

- String Operations using Pointers

- Example: String copy

```
void Copy(
    const char *Dst,
    const char *Src)
{
    do{
        *Dst = *Src;
        Dst++;
    } while(*Src++);
}
```

```
char s1[] = "ABC";
char s2[] = "Hello World!";

printf("s1 is %s, s2 is %s\n",
      s1, s2);
Copy(s2, s1);
printf("s1 is %s, s2 is %s\n",
      s1, s2);
```

```
s1 is ABC, s2 is Hello World!
s1 is ABC, s2 is ABC
```

Error!
Write access to
const data!

- Passing pointers as arguments to functions

- Function can modify caller data by pointer dereferencing
- Type qualifier **const**:
Modification by pointer dereferencing *not* allowed!

Standard Library Functions

- Functions declared in `string.h` (part 1/2)

- `typedef unsigned int size_t;`
 - type definition for length of strings
- `size_t strlen(const char *s);`
 - returns the length of string `s`
- `int strcmp(const char *s1, const char *s2);`
 - alphabetically compares string `s1` with string `s2`
 - returns -1 / 0 / 1 for less-than / equal-to / greater-than
- `int strncmp(const char *s1, const char *s2, size_t n);`
 - same as previous, but compares maximal `n` characters
- `int strcasecmp(const char *s1, const char *s2);`
- `int strncasecmp(const char *s1, const char *s2, size_t n);`
 - same as string comparisons above, but case-insensitive

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Standard Library Functions

- Functions declared in `string.h` (part 2/2)

- `char *strcpy(char *s1, const char *s2);`
 - copies string `s2` into string `s1`
- `char *strncpy(char *s1, const char *s2, size_t n);`
 - copies maximal `n` characters of string `s2` into string `s1`
- `char *strcat(char *s1, const char *s2);`
 - concatenates string `s2` to string `s1`
- `char *strncat(char *s1, const char *s2, size_t n);`
 - concatenates maximal `n` characters of string `s2` to string `s1`
- `char *strchr(const char *s, int c);`
 - returns a pointer to the first character `c` in string `s`, or `NULL` if not found
- `char *strrchr(const char *s, int c);`
 - returns a pointer to the last character `c` in string `s`, or `NULL` if not found
- `char *strstr(const char *s1, const char *s2);`
 - returns a pointer to the first appearance of `s2` in string `s1` (or `NULL`)

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File Processing

- Introduction
 - Up to now, all data processed is available only during program run time
 - At program completion, all data is lost
 - *Persistent data* is stored even after a program exits
 - Persistent data is stored in files...
 - ... on the harddisk
 - ... on a removable disk (CD, memory stick, ...)
 - ... on a tape, ...
 - Input and output from/to files is organized as *I/O streams*

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File Processing

- I/O Streams
 - Standard I/O streams (opened by the system)
 - `stdin` standard input stream (i.e. `scanf()`)
 - `stdout` standard output stream (i.e. `printf()`)
 - `stderr` standard error stream (i.e. `perror()`)
 - File I/O streams (explicitly opened by a program)
 - Open a file `fopen()`
 - Write data to a file `fprintf()`, `fputs()`, etc.
 - Read data from a file `fscanf()`, `fgets()`, etc.
 - Close a file `fclose()`
 - In C, all I/O functions are ...
 - ... declared in header file `stdio.h`
 - ... implemented in the standard C library

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Standard I/O Functions

- Functions declared in `stdio.h` (part 1/4)
 - `int printf(const char *fmt, ...);`
 - `int scanf(const char *fmt, ...);`
 - formatted output/input to/from stream `stdin/stdout`
 - `int sprintf(char *s, const char *fmt, ...);`
 - `int sscanf(const char *s, const char *fmt, ...);`
 - formatted output/input to/from a string `s`
 - `int getchar(void);`
 - `int putchar(int c);`
 - input/output of a single character to/from stream `stdin/stdout`
 - `char *gets(char *s);`
 - `int puts(const char *s);`
 - input/output of strings to/from stream `stdin/stdout`

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Standard I/O Functions

- Functions declared in `stdio.h` (part 2/4)
 - `typedef __FILE FILE;`
 - opaque type for a file handle
 - `FILE *fopen(const char *n, const char *m);`
 - open file named `n` for input ("`r`"), output ("`w`"), or append ("`a`")
 - returns a file handle, or `NULL` in case of an error
 - `int fclose(FILE *f);`
 - closes an open file handle
 - `int fprintf(FILE *f, const char *fmt, ...);`
 - `int fscanf(FILE *f, const char *fmt, ...);`
 - `int fgetc(FILE *f);`
 - `char *fgets(char *s, int n, FILE *f);`
 - `int fputc(int c, FILE *f);`
 - `int fputs(const char *s, FILE *f);`
 - input/output functions from/to stream `f`
 - `int fflush(FILE *f);`
 - flushes any unwritten data from a buffer into the file

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Standard I/O Functions

- Functions declared in `stdio.h` (part 3/4)
 - `typedef unsigned int size_t;`
 - type for size of a block of memory (number of bytes)
 - `size_t fread(void *p, size_t s, size_t n, FILE *f);`
 - binary input to memory location `p` for `n` times `s` bytes from file `f`
 - `size_t fwrite(const void *p, size_t s, size_t n, FILE *f);`
 - binary output from memory location `p` for `n` times `s` bytes to file `f`
 - `int fseek(FILE *f, long pos, int w);`
 - move to position `pos` in file `f` (from beginning/current pos/end)
 - `long ftell(FILE *f);`
 - return the current position in file `f` (from beginning)
 - `void rewind(FILE *f);`
 - move to beginning of file `f`
 - `int feof(FILE *f);`
 - check if end of file `f` is reached

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Standard Library Functions

- Functions declared in `stdio.h` (part 4/4)
 - `int ferror(FILE *f);`
 - returns the current error status for file `f`
 - `void perror(const char *prg);`
 - print current error for program `prg` to stream `stderr`
 - `int remove(const char *filename);`
 - delete file `filename`
 - `int rename(const char *old, const char *new);`
 - rename file `old` to new name `new`

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File Processing

- Program example: **PhotoLab**
 - Digital image manipulation
 - Read an image from a file
 - Manipulate the image in memory
 - Write the modified image to file
 - Portable Pixel Map (PPM) file format
 - simple uncompressed file format for color images
 - Header section (including picture width, height)
 - Data section (pixel values in Red/Green/Blue format)

```
P6
800 450
255
RGBRGBRGB...
```

File Processing

- Program example: **PhotoLab.c** (part 1/10)

```

/*****
/* PhotoLab.c: final assignment for EECS 10 in Fall 2007 */
/*
/* modifications: (most recent first)
/* 12/01/07 RD adjusted for lecture usage
/*****

#include <stdio.h>
#include <stdlib.h>

/** global definitions **/

#define WIDTH 800 /* image width */
#define HEIGHT 450 /* image height */
#define SLEN 80 /* max. string length */

...

```

File Processing

- Program example: PhotoLab.c (part 2/10)

```

...
/** function definitions */
/* write the RGB image to a PPM file */
/* (return 0 for success, >0 for error) */
int SaveImage(char fname[SLEN],
              unsigned char R[WIDTH][HEIGHT],
              unsigned char G[WIDTH][HEIGHT],
              unsigned char B[WIDTH][HEIGHT])
{
    FILE *File;
    int x, y;
    File = fopen(fname, "w");
    if (!File)
    { printf("\nCannot open file \"%s\"!\n", fname);
      return(1);
    }
    ...

```

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File Processing

- Program example: PhotoLab.c (part 3/10)

```

...
fprintf(File, "P6\n");
fprintf(File, "%d %d\n", WIDTH, HEIGHT);
fprintf(File, "255\n");
for(y=0; y<HEIGHT; y++)
{ for(x=0; x<WIDTH; x++)
  { fputc(R[x][y], File);
    fputc(G[x][y], File);
    fputc(B[x][y], File);
  }
}
if (ferror(File))
{ printf("\nFile error while writing to file!\n");
  return(2);
}
fclose(File);
return(0); /* success! */
} /* end of SaveImage */
...

```

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File Processing

- Program example: PhotoLab.c (part 4/10)

```

...
/* read an image file into the RGB data structure */
/* (return 0 for success, >0 for error) */

int ReadImage(char fname[SLEN],
              unsigned char R[WIDTH][HEIGHT],
              unsigned char G[WIDTH][HEIGHT],
              unsigned char B[WIDTH][HEIGHT])
{
    FILE *File;
    char Type[SLEN];
    int Width, Height, MaxValue, x, y;

    File = fopen(fname, "r");
    if (!File)
    { printf("\nCannot open file \"%s\"\n", fname);
      return(1);
    }
    ...

```

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File Processing

- Program example: PhotoLab.c (part 5/10)

```

...
fscanf(File, "%79s", Type);
if (Type[0] != 'P' || Type[1] != '6' || Type[2] != 0)
{ printf("\nUnsupported file format!\n");
  return(2);
}
fscanf(File, "%d", &Width);
if (Width != WIDTH)
{ printf("\nUnsupported image width %d!\n", Width);
  return(3);
}
fscanf(File, "%d", &Height);
if (Height != HEIGHT)
{ printf("\nUnsupported image height %d!\n", Height);
  return(4);
}
...

```

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File Processing

- Program example: PhotoLab.c (part 6/10)

```
...
fscanf(File, "%d", &MaxValue);
if (MaxValue != 255)
{   printf("\nUnsupported maximum %d!\n", MaxValue);
    return(5);
}
if ('\n' != fgetc(File))
{   printf("\nCarriage return expected!\n");
    return(6);
}
for(y=0; y<HEIGHT; y++)
{   for(x=0; x<WIDTH; x++)
    {   R[x][y] = fgetc(File);
        G[x][y] = fgetc(File);
        B[x][y] = fgetc(File);
    }
}
...
```

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File Processing

- Program example: PhotoLab.c (part 7/10)

```
...
if (ferror(File))
{   printf("\nFile error while reading from file!\n");
    return(7);
}
fclose(File);
return(0); /* success! */
} /* end of ReadImage */
...
```

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File Processing

- Program example: PhotoLab.c (part 8/10)

```
...
/* modify the image... ;-) */

void ModifyImage(unsigned char R[WIDTH][HEIGHT],
                unsigned char G[WIDTH][HEIGHT],
                unsigned char B[WIDTH][HEIGHT])
{
    int x, y;

    for(y=0; y<HEIGHT; y++)
    {
        for(x=0; x<WIDTH; x++)
        {
            R[x][y] = R[x][(HEIGHT+y)/2];
            G[x][y] = G[x][(HEIGHT+y)/2];
            B[x][y] = B[x][(HEIGHT+y)/2];
        }
    }
}

/* end of ModifyImage */
...
```

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File Processing

- Program example: PhotoLab.c (part 9/10)

```
...
/** main program ***/

int main(void)
{
    /* image data */
    unsigned char R[WIDTH][HEIGHT];
    unsigned char G[WIDTH][HEIGHT];
    unsigned char B[WIDTH][HEIGHT];
    /* file name */
    char fname[SLEN];

    ...
}
```

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File Processing

- Program example: PhotoLab.c (part 10/10)

```

...
printf("Enter input file name: ");
scanf("%79s", fname);
if (ReadImage(fname, R,G,B) != 0)
{ exit(10); }

/* modify the image */
ModifyImage(R, G, B);

printf("Enter output file name: ");
scanf("%79s", fname);
if (SaveImage(fname, R,G,B) != 0)
{ exit(10); }

return 0;
} /* end of main */

/* EOF */

```

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File Processing

- Example session:

```

% vi PhotoLab.c
% gcc PhotoLab.c -o PhotoLab -Wall -ansi
% PhotoLab
Enter input file name: imgColor.ppm
Enter output file name: newFile.ppm
%

```



imgColor.ppm



newFile.ppm

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Translation Units

- Introduction
 - C compilation process is a sequence of phases
 - Preprocessing (handle # directives)
 - Scanning and parsing (generate internal data structure)
 - Instruction generation (emit stream of CPU instructions)
 - Assembly (generate binary object file)
 - Linking (combine objects into executable file)
 - C compiler consists of separate components
 - Preprocessor (processes # directives)
 - Compiler (compiles and assembles code)
 - Linker (processes object files and libraries)

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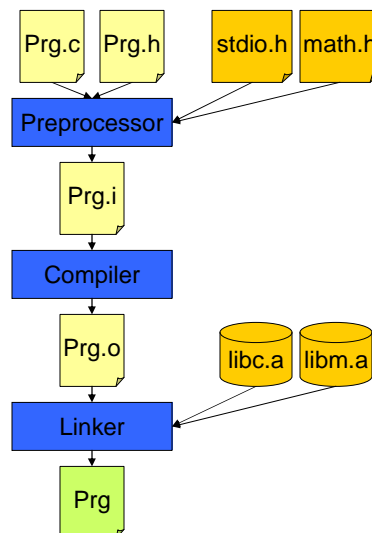
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Translation Units

- Compilation Phases

- Source code
 - Program file
 - Header file(s)
- Preprocessed file
- Object file
- Library file(s)
- Executable file



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Translation Units

- Source files
 - Header files: **Program.h**
 - Inclusion of required header files
 - Definitions of exported constants
 - Declarations of exported global variables
 - Declarations of exported functions
 - Program files: **Program.c**
 - Inclusion of required header files
 - Declaration and definition of local variables
 - Declaration and definition of local functions
 - Definitions of exported global variables
 - Definitions of exported functions

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Translation Units

- C Preprocessor
 - preprocesses source files
 - handles # directives
- Preprocessing Directives
 - Constant definition
 - Macro definition
 - Header file inclusion
 - Conditional compilation

```
#define WIDTH 800
```

```
#define ABS(x) (x>0 ? x : -x)
```

```
#include <stdio.h>
```

```
#define DEBUG /* comment out to turn debugging off */
...
#ifdef DEBUG
printf("value of x is now %d\n", x);
#endif
```

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Translation Units

- Object files
 - **Program.o**
 - Compiled object code of source file **Program.c**
 - Use option `-c` in GNU compiler call to create object files
`gcc -c Program.c -o Program.o -Wall -ansi`
 - **Library.a**
 - Archive of compiled object files
- Executable file
 - **Program**
 - Object files and libraries linked together into a complete file ready for execution
 - GNU compiler recognizes object files by `.o` suffix, so object files and libraries require no special option
`gcc Program.o -lc -lm -o Program`

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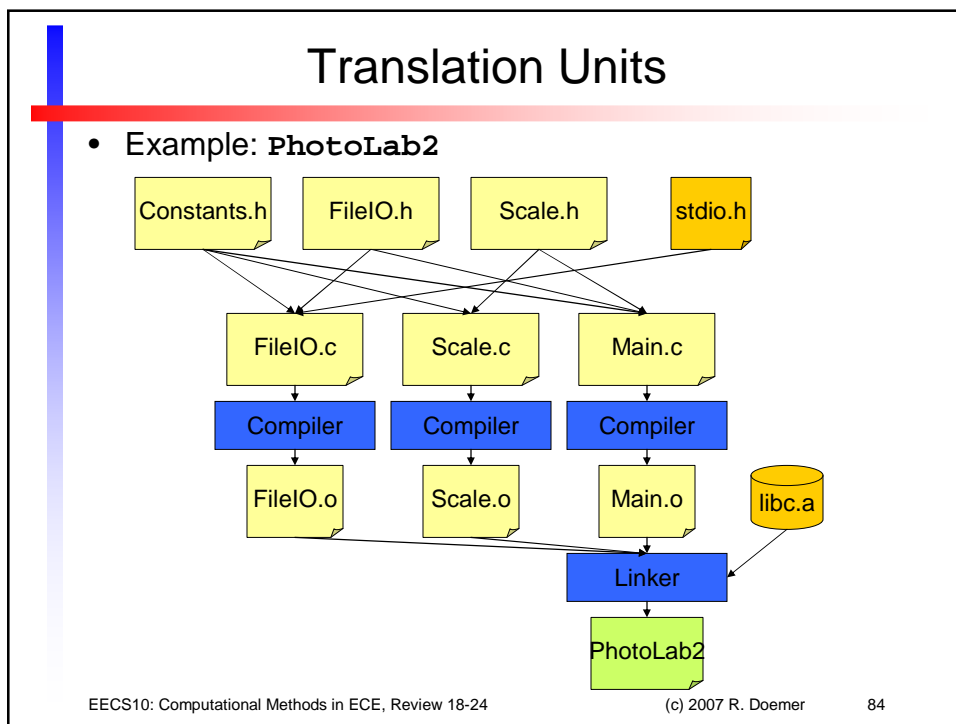
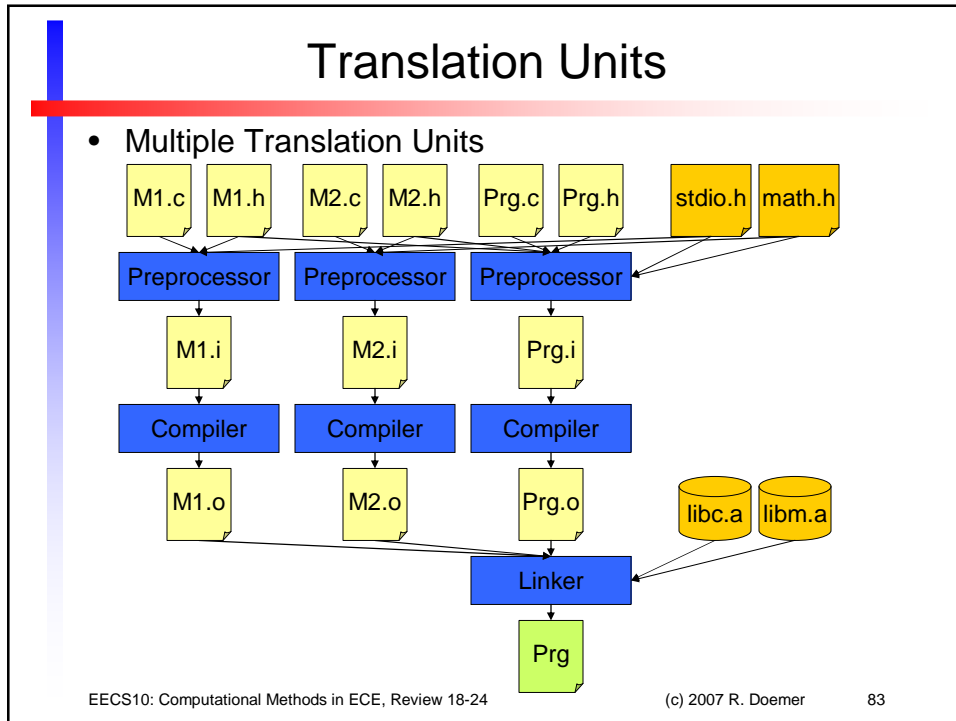
Translation Units

- Multiple Translation Units
 - C programs can be partitioned into multiple translation units, aka. *modules*
 - Modules typically consist of
 - Module header file (file suffix `.h`)
 - Module program file (file suffix `.c`)
 - Module object file (file suffix `.o`)
 - Modules are *linked* together
 - Linker combines object files and required libraries into an executable file
 - `gcc Program.o Mod1.o Mod2.o -lc -lm -o Program`

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Translation Units

- Example: Header file `Constants.h`

```

/*****
/* Constants.h: header file for constant definitions */
/* author: Rainer Doemer */
/* modifications: (most recent first) */
/* 12/02/07 RD version for Fall 2007 */
*****/

#ifndef CONSTANTS_H
#define CONSTANTS_H

/** global definitions */

#define WIDTH 800 /* image width */
#define HEIGHT 450 /* image height */
#define SLEN 80 /* max. string length */

#endif /* CONSTANTS_H */

/* EOF Constants.h */

```

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Translation Units

- Example: Header file `FileIO.h`

```

/*****
/* FileIO.h: header file for I/O module */
*****/

#ifndef FILE_IO_H
#define FILE_IO_H

#include "Constants.h"

int ReadImage( /* read image from file */
    char Filename[SLEN],
    unsigned char R[WIDTH][HEIGHT],
    unsigned char G[WIDTH][HEIGHT],
    unsigned char B[WIDTH][HEIGHT]);

int SaveImage( /* write image to file */
    char Filename[SLEN],
    unsigned char R[WIDTH][HEIGHT],
    unsigned char G[WIDTH][HEIGHT],
    unsigned char B[WIDTH][HEIGHT]);

#endif /* FILE_IO_H */

/* EOF FileIO.h */

```

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Translation Units

- Example: Program file `FileIO.c`

```

/*****
/* FileIO.c: program file for I/O module */
*****/

#include <stdio.h>
#include "FileIO.h"

/**/ function definitions ***/

int ReadImage(char Filename[SLEN],
              unsigned char R[WIDTH][HEIGHT],
              unsigned char G[WIDTH][HEIGHT],
              unsigned char B[WIDTH][HEIGHT])
{ /* ... function body ... */
}

int SaveImage(char Filename[SLEN],
              unsigned char R[WIDTH][HEIGHT],
              unsigned char G[WIDTH][HEIGHT],
              unsigned char B[WIDTH][HEIGHT])
{ /* ... function body ... */
}

EECS /* EOF FileIO.c */

```

Translation Units

- Example: Header file `scale.h`

```

/*****
/* Scale.h: header file for scaling operation */
*****/

#ifndef SCALE_H
#define SCALE_H

/**/ header files ***/
#include "Constants.h"

/**/ function declarations ***/

void Scale( /* scale the image */
           unsigned char R[WIDTH][HEIGHT],
           unsigned char G[WIDTH][HEIGHT],
           unsigned char B[WIDTH][HEIGHT],
           double      ScaleFactor);

#endif /* SCALE_H */

/* EOF Scale.h */

```

Translation Units

- Example: Program file `scale.c`

```

/*****
/* Scale.c: program file for scaling operation */
/*****

#include "Scale.h"

/** function definitions */
/* scale the image vertically */
void Scale(
    unsigned char R[WIDTH][HEIGHT],
    unsigned char G[WIDTH][HEIGHT],
    unsigned char B[WIDTH][HEIGHT],
    double        ScaleFactor)
{
    /* ... function body ... */
}

/* EOF Scale.c */

```

Translation Units

- Example: Program file `Main.c`

```

/*****
/* Main.c: main program file */
/*****

#include "Constants.h"
#include "FileIO.h"
#include "Scale.h"

int main(void)
{
    unsigned char R[WIDTH][HEIGHT];
    unsigned char G[WIDTH][HEIGHT];
    unsigned char B[WIDTH][HEIGHT];

    if(ReadImage("Input.ppm", R, G, B) != 0)
    { exit(10); }
    Scale(R, G, B, 2.0);
    if (SaveImage("Output.ppm", R, G, B) != 0)
    { exit(10); }

    return 0;
} /* end of main */
/* EOF Main.c */

```

Translation Units

- Example session:

```
% vi Constants.h  
% vi FileIO.h  
% vi FileIO.c  
% vi Scale.h  
% vi Scale.c  
% vi Main.c
```

```
% gcc -c FileIO.c -o FileIO.o -Wall -ansi  
% gcc -c Scale.c -o Scale.o -Wall -ansi  
% gcc -c Main.c -o Main.o -Wall -ansi  
% gcc FileIO.o Scale.o Main.o -o PhotoLab2  
% PhotoLab2  
%
```



Input.ppm



Output.ppm