Class Announcements

- First programming project has been posted. Code base is available in Files/Projects on canvas. Deadline: Friday, March 24 (week after spring break). START WORKING ON PROJECT NOW!

  Late submission policy: 20% penalty for every 24 hour period after the submission deadline.

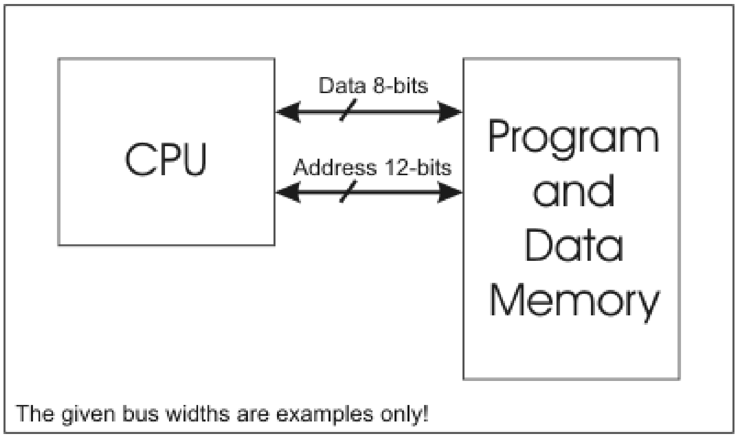
- Reminder: There are no late submissions for homeworks. Homeworks are preparation for exams. The two lowest grade homeworks out of all homeworks offered will be dropped. If you do not turn in a homework, you will receive 0 points on that homework.
- Reminder: Two exams will count out of three offered. The lowest exam grade will be dropped. If you do not take an exam, you will receive 0 points on that exam. There are no make-up exams.

Imperative Programming Languages

Imperative:

Sequence of state-changing actions.

- Manipulate an abstract machine with:
  1. Variables naming memory locations
  2. Arithmetic and logical operations
  3. Reference, evaluate, assign operations
  4. Explicit control flow statements
- Key operations: *Assignment* and "*Goto*"
- Fits the von Neumann architecture closely

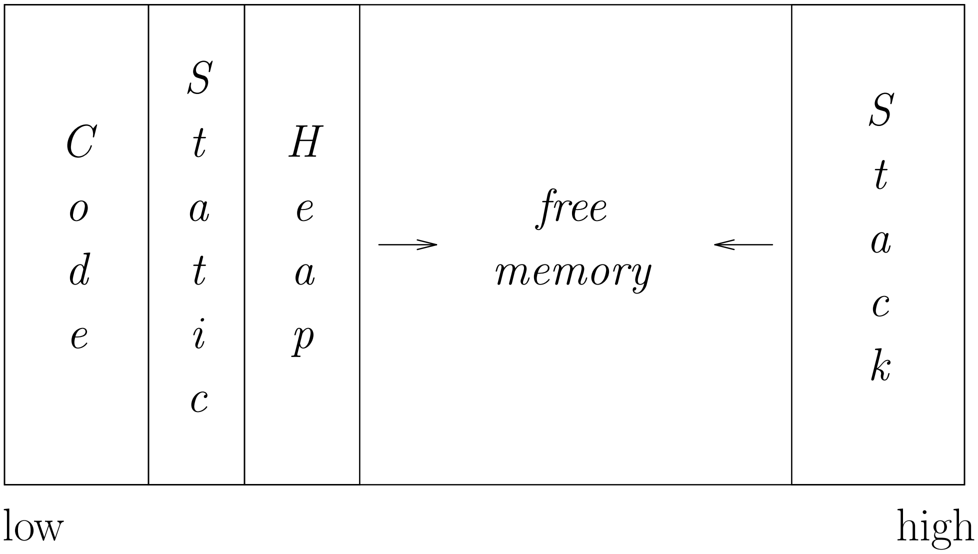


Von Neumann Architecture

Run-time storage organization

Typical memory layout

Logical Address Space



Code

Static

Heap

→ *free memory* ←

Stack

low

high

The classical scheme

- allows both stack and heap maximal freedom
- code and static may be separate or intermingled

Will talk about this in more detail in a later lecture!

C: An Imperative Programming Language

Expressions: include procedure and function calls and assignments, and thus can have side-effects

Control Structures:

- if statements, with and without else clauses
- loops, with break and continue exits

```
while ( <expr> ) <stmt>
do <stmt> while ( <expr> )
for ( <expr> ; <expr> ; <expr> ) <stmt>
```

- switch statements
- goto with labelled branch targets

C Examples

```
while ( ( c = getchar()) != EOF ) putchar(c);
```

```
for ( i = 0 ; s[i] == ’ ’ ; i++ );
```

```
for ( i = 0 ; i < n ; i++ ) {
  if ( a[i] < 0 ) continue; /*skip neg elems*/
  ....
}
```

```
c = getchar();
switch(c) {
     case ’0’: case ’1’: case ’2’: case ’3’:
     case ’4’: case ’5’: case ’6’: case ’7’:
     case ’8’: case ’9’:
        digit[c-’0’]++;
        break;
     case ’ ’: case ’\n’: case ’\t’:
        delim++;
        break;
     ...
 }
```

Data Types in C

- Primitives: `char`, `int`, `float`, `double`
  no Boolean—any nonzero value is true
- Aggregates: arrays, structures

```
char a[10], b[2][10];

struct rectangle {
   struct point p1;
   struct point p2;
}
```

- Enumerations: collection of sequenced values
- Pointers:

`&i`	address of i
`*p`	dereferenced value of p
`p+1`	pointer arithmetic

```
int *p, i;
p = &i;
*p = *p + 1;
```

Basic Comparison (incomplete!)

C	Java
Basic types: int, double, char	Primitive types: int, double, char, **boolean**
Pointer (to a value)	**Reference (to an object)**
Aggregates: array, **struct**	Aggregates: array, object (**class**)
Control flow: if-else, switch, while, break, continue, for, return, **goto**	Control flow if-else, switch, while, break, continue, for, return
Logic operators: ||, &&, !	Logic operators: ||, &&, !
Logical comparisons: ==, !=	Logical comparisons: ==, !=
Numeric comparisons: <>, <=, >=	Numeric comparisons: <>, <=, >=
string as **char * array**	**String** as an object

Compile and Run a C program

`test.c`:

```
#include <stdio.h>

int
main(void)
{
  int x, y;

  printf("First number:\n"); scanf("%d", &x);
  printf("Second number:\n"); scanf("%d", &y);

  printf("%d+%d = %d\n", x, y, x+y);
  printf("%d-%d = %d\n", x, y, x-y);
  printf("%d*%d = %d\n", x, y, x*y);

  return 0;
}
```

`gcc test.c`:	calls the GNU C compiler, and generates executable `a.out`
`./a.out`	runs the executable
`gcc -o run test.c`	compiles program, and generates executable `run`
`gcc -g test.c`	generates `a.out` with debugging info
`gdb a.out`	run debugger on `a.out`; online documentation `man gdb`

Compile and Run a C program

```
> gcc test.c
> a.out
First number:
4
Second number:
12
4+12 = 16
4-12 = -8
4*12 = 48
>
```

START PROGRAMMING IN C NOW!

Debugging C programs

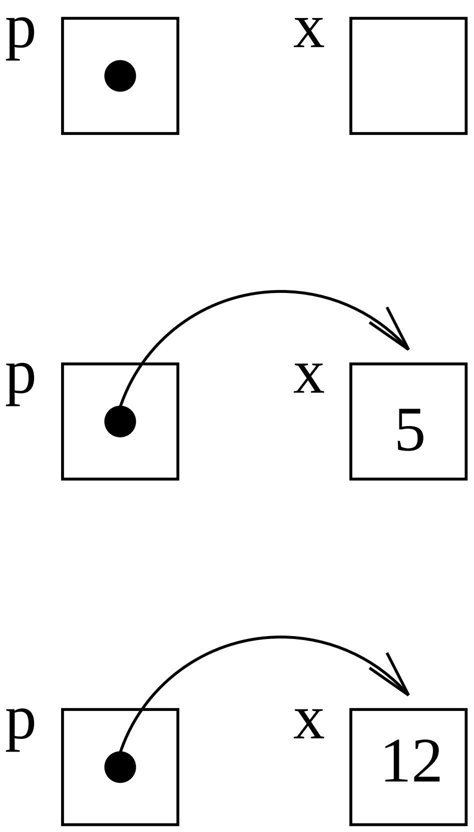
```
rhea% gdb a.out
(gdb) list
1       #include <stdio.h>
2       int main(void)
3       {
4         int x, y;
5         printf("First number:\n"); scanf("%d", &x);
6         printf("Second number:\n"); scanf("%d", &y);
7         printf("%d+%d = %d\n", x, y, x+y);
(gdb) break 7
Breakpoint 1 at 0x1052c: file test.c, line 7.
(gdb) run
Starting program: /.../a.out
First number:
4
Second number:
12
Breakpoint 1, main () at test.c:7
7         printf("%d+%d = %d\n", x, y, x+y);
(gdb) print x
$1 = 4
(gdb) print y
$2 = 12
(gdb) cont
Continuing.
4+12 = 16
4-12 = -8
4*12 = 48
Program exited normally.
(gdb) quit
```

Pointers in C

Pointer: Variable whose R-values (content) is the L-value (address) of a variable

- “address-of” operator &
- dereference (“content-of”) operator $*$

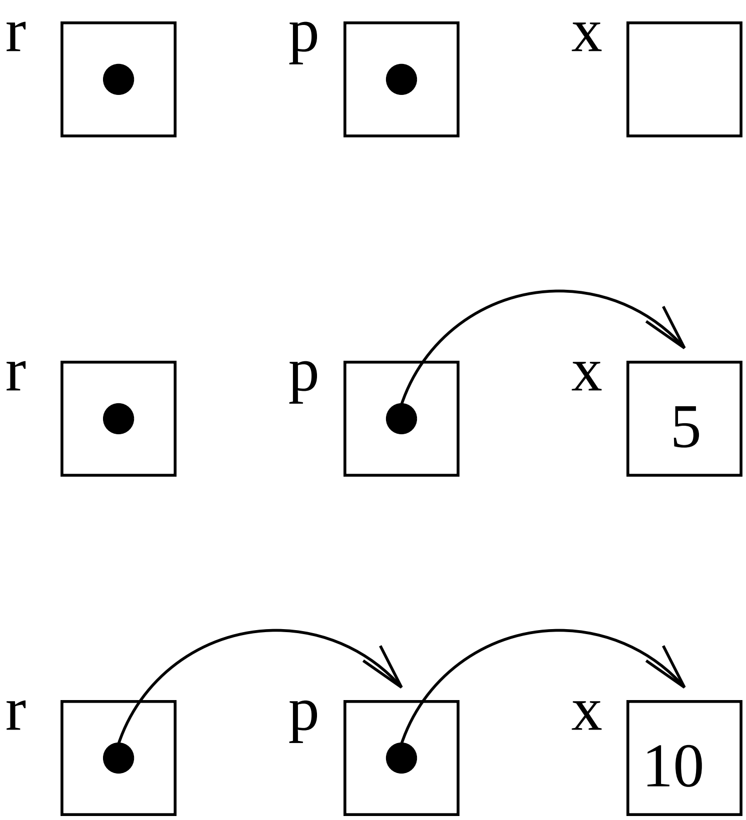
```
int *p, x;

 p = &x;
*p = 5;

 x = 12;
```



Pointers in C

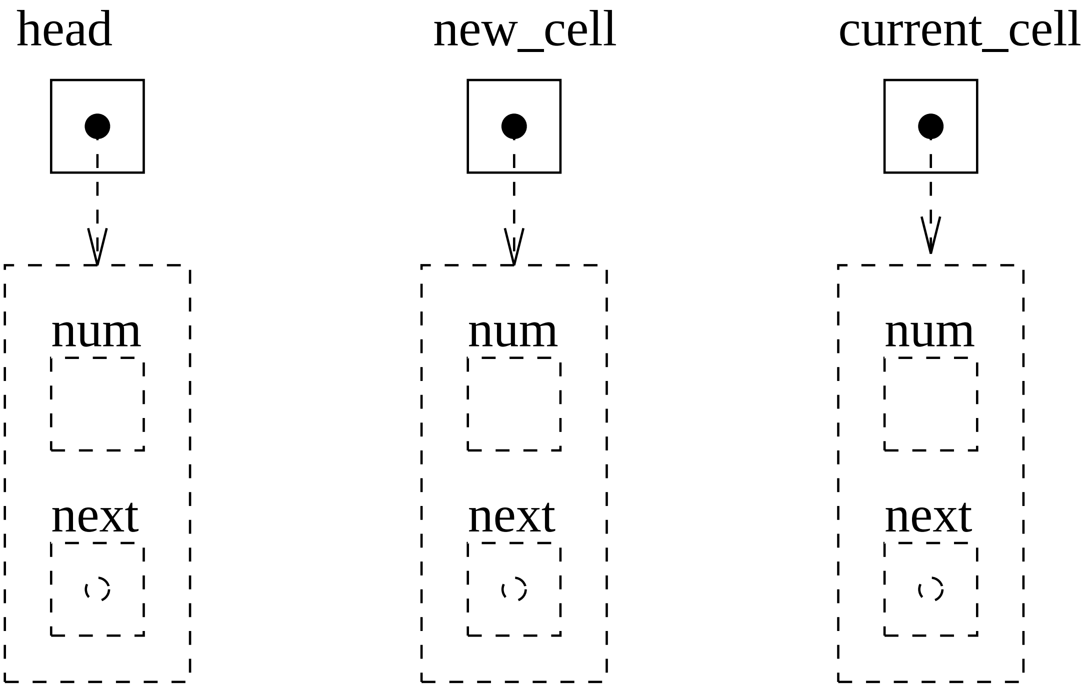
- Pointers can point to pointer variables (multi-level pointers)

```
int *p, x;
int **r;

p = &x;
*p = 5;

r = &p;
**r = 10;
```



Example: Singly-linked list

```
#include <stdio.h>
#include <stdlib.h>
/* TYPE DEFINITION */
typedef struct cell listcell;
struct cell
{ int num;
  listcell *next;
};

/* GLOBAL VARIABLES */
  listcell *head, *new_cell, *current_cell;
```

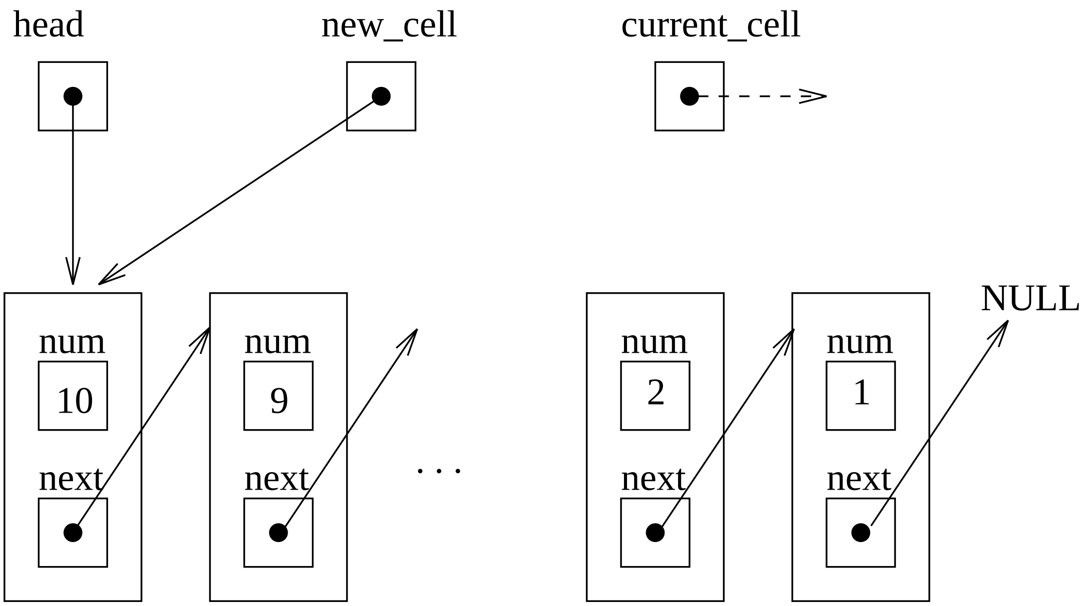


Example: Singly-linked list

```
int main (void)
{
  int j;

  /* CREATE FIRST LIST ELEMENT */
  head = (listcell *) malloc(sizeof(listcell));
  head->num = 1;
  head->next = NULL;

  /* CREATE 9 MORE ELEMENTS */
  for (j=2; j<=10; j++) {
    new_cell = (listcell *) malloc(sizeof(listcell));
    new_cell->num = j;
    new_cell->next = head;
    head = new_cell;
  }

  /* PRINT ALL ELEMENTS */
  for (current_cell = head;
       current_cell != NULL;
       current_cell = current_cell->next)
    printf("%d ", current_cell->num);

  printf("\n");
}
```

Example: Singly-linked list

```
int main (void)
{
  int j;

  /* CREATE FIRST LIST ELEMENT */
  head = (listcell *) malloc(sizeof(listcell));
  head->num = 1;
  head->next = NULL;

  /* CREATE 9 MORE ELEMENTS */
  for (j=2; j<=10; j++) {
    new_cell = (listcell *) malloc(sizeof(listcell));
    new_cell->num = j;
    new_cell->next = head;
    head = new_cell;
  }
     /* *** HERE *** */
```



Example: Singly-linked list

- What is the output of the program
- Where do the cell objects get allocated?

Review: Stack vs. Heap

Stack:

- Procedure activations, statically allocated local variables, parameter values
- Lifetime same as subroutine in which variables are declared
- Stack frame is pushed with each invocation of a subroutine, and poped after subroutine exit

Heap:

- Dynamically allocated data structures, whose size may not be known in advance
- Lifetime extends beyond subroutine in which they are created
- Must be explicitly freed or garbage collected

Next Lecture

Things to do:

Start working on the project!

Read Scott: Chap. 3.1 - 3.4; 8.3 ; ALSU Chap. 7.1 - 7.3

Next time:

- Dynamic memory allocation: malloc and free
- What can go wrong
- Static and dynamic scoping
- Activation records, maintaining a lexically scoped runtime environment using access links and displays.
- Parameter passing styles and their implementations.