C and C++

3. Pointers — Structures

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(heavily based on last year's notes (Andrew Moore) with thanks to Alastair R. Beresford and Bjarne Stroustrup)

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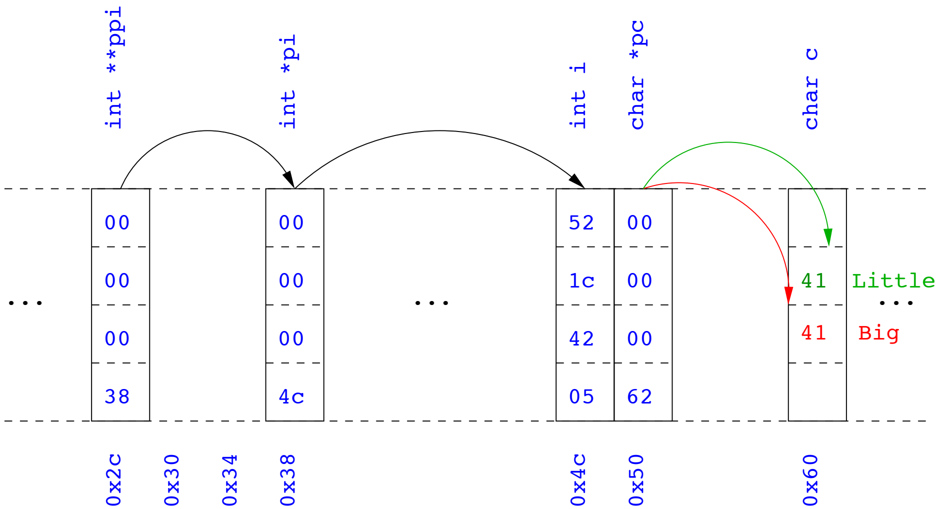
Pointers

- Computer memory is often abstracted as a sequence of bytes, grouped into words
- Each byte has a unique address or index into this sequence
- The size of a word (and byte!) determines the size of addressable memory in the machine
- A pointer in C is a variable which contains the memory address of another variable (this can, itself, be a pointer)
- Pointers are declared or defined using an asterisk(*); for example: `char *pc;` or `int **ppi;`
- The asterisk binds to the variable name, not the type definition; for example `char *pc,c;`
- A pointer does not necessarily take the same amount of storage space as the type it points to

Example



Manipulating pointers

- The value "pointed to" by a pointer can be "retrieved" or dereferenced by using the unary * operator; for example:
  ```
  int *p = ...
  int x = *p;
  ```
- The memory address of a variable is returned with the unary ampersand (&) operator; for example
  ```
  int *p = &x;
  ```
- Dereferenced pointer values can be used in normal expressions; for example: `*pi += 5;` or `(*pi)++`

Example

```c
#include <stdio.h>

int main(void) {
  int x=1,y=2;
  int *pi;
  int **ppi;

  pi = &x; ppi = &pi;
  printf("%p, %p, %d=%d=%d\n",ppi,pi,x,*pi,**ppi);
  pi = &y;
  printf("%p, %p, %d=%d=%d\n",ppi,pi,y,*pi,**ppi);

  return 0;
}
```


Pointers and arrays

- A C array uses consecutive memory addresses without padding to store data
- An array name (without an index) represents the memory address of the beginning of the array; for example:
  `char c[10];`
  `char *pc = c;`
- Pointers can be used to "index" into any element of an array; for example:
  `int i[10];`
  `int *pi = &i[5];`

Pointer arithmetic

- Pointer arithmetic can be used to adjust where a pointer points; for example, if `pc` points to the first element of an array, after executing `pc+=3;` then `pc` points to the fourth element
- A pointer can even be dereferenced using array notation; for example `pc[2]` represents the value of the array element which is two elements beyond the array element currently pointed to by `pc`
- In summary, for an array `c`, `*(c+i)≡c[i]` and `c+i≡&c[i]`
- A pointer is a variable, but an array name is not; therefore `pc=c` and `pc++` are valid, but `c=pc` and `c++` are not

Example

```c
#include <stdio.h>

int main(void) {
  char str[] = "A string.";
  char *pc = str;

  printf("%c %c %c\n",str[0],*pc,pc[3]);
  pc += 2;
  printf("%c %c %c\n",*pc, pc[2], pc[5]);

  return 0;
}
```

Pointers as function arguments

- Recall that all arguments to a function are copied, i.e. passed-by-value; modification of the local value does not affect the original
- In the second lecture we defined functions which took an array as an argument; for example `void reverse(char s[])`
- Why, then, does `reverse` affect the values of the array after the function returns (i.e. the array values haven't been copied)?
  - because `s` is a pointer to the start of the array
- Pointers of any type can be passed as parameters and return types of functions
- Pointers allow a function to alter parameters passed to it

Example

- Compare `swp1(a,b)` with `swp2(&a,&b)`:

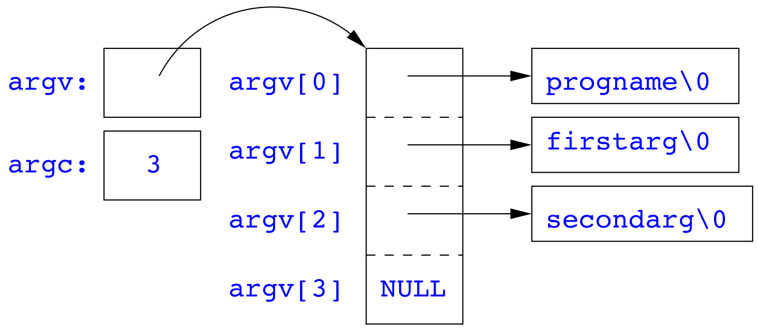
```
void swp1(int x,int y)
{
  int temp = x;
  x = y;
  y = temp;
}
```

```
void swp2(int *px,int *py)
{
  int temp = *px;
  *px = *py;
  *py = temp;
}
```


Arrays of pointers

- C allows the creation of arrays of pointers; for example `int *a[5];`
- Arrays of pointers are particularly useful with strings
- An example is C support of command line arguments: `int main(int argc, char *argv[]) { ... }`
- In this case `argv` is an array of character pointers, and `argc` tells the programmer the length of the array

Example



Multi-dimensional arrays

- Multi-dimensional arrays can be declared in C; for example: `int i[5][10];`
- Values of the array can be accessed using square brackets; for example: `i[3][2]`
- When passing a two dimensional array to a function, the first dimension is not needed; for example, the following are equivalent:

```
void f(int i[5][10]) { ... }
void f(int i[][10])  { ... }
void f(int (*i)[10]) { ... }
```

- In arrays with higher dimensionality, all but the first dimension must be specified

Pointers to functions

- C allows the programmer to use pointers to functions
- This allows functions to be passed as arguments to functions
- For example, we may wish to parameterise a sort algorithm on different comparison operators (e.g. lexicographically or numerically)
- If the sort routine accepts a pointer to a function, the sort routine can call this function when deciding how to order values

Example

```
void sort(int a[], const int len,
          int (*compare)(int, int))
{
  int i,j,tmp;
  for(i=0;i<len-1;i++)
    for(j=0;j<len-1-i;j++)
      if ((*compare)(a[j],a[j+1]))
       tmp=a[j], a[j]=a[j+1], a[j+1]=tmp;
}

int inc(int a, int b) {
  return a > b ? 1 : 0;
}
```


Example

```
#include <stdio.h>
#include "example8.h"

int main(void) {
  int a[] = {1,4,3,2,5};
  unsigned int len = 5;
  sort(a,len,inc); //or sort(a,len,&inc);

  int *pa = a; //C99
  printf("[");
  while (len--)
    printf("%d%s",*pa++,len?" ":"");
  printf("]\n");

  return 0;
}
```

The void * pointer

- C has a "typeless" or "generic" pointer: `void *p`
- This can be a pointer to anything
- This can be useful when dealing with dynamic memory
- Enables "polymorphic" code; for example:

```
sort(void *p, const unsigned int len,
     int (*comp)(void *,void *));
```

- However this is also a big "hole" in the type system
- Therefore `void *` pointers should only be used where necessary

Structure declaration

- A structure is a collection of one or more variables
- It provides a simple method of abstraction and grouping
- A structure may itself contain structures
- A structure can be assigned to, as well as passed to, and returned from functions
- We declare a structure using the keyword `struct`
- For example, to declare a structure `circle` we write
  `struct circle {int x; int y; unsigned int r;};`
- Once declared, a structure creates a new type

Structure definition

- To define an instance of the structure `circle` we write
  `struct circle c;`
- A structure can also be initialised with values:
  `struct circle c = {12, 23, 5};`
- An automatic, or local, structure variable can be initialised by function call:
  `struct circle c = circle_init();`
- A structure can declared, and several instances defined in one go:
  `struct circle {int x; int y; unsigned int r;} a, b;`

Member access

- A structure member can be accessed using '`.`' notation:
  structname`.`member; for example: `pt.x`
- Comparison (e.g. `pt1 > pt2`) is undefined
- Pointers to structures may be defined; for example:
  `struct circle *pc`
- When using a pointer to a struct, member access can be achieved with the '`.`' operator, but can look clumsy; for example: `(*pc).x`
- Alternatively, the '`->`' operator can be used; for example: `pc->x`

Self-referential structures

- A structure declaration can contain a member which is a pointer whose type is the structure declaration itself
- This means we can build recursive data structures; for example:

```
struct tree {
 int val;
 struct tree *left;
 struct tree *right;
}
```

```
struct link {
 int val;
 struct link *next;
}
```


Unions

- A union variable is a single variable which can hold one of a number of different types
- A union variable is declared using a notation similar to structures; for example: `union u { int i; float f; char c;};`
- The size of a union variable is the size of its largest member
- The type held can change during program execution
- The type retrieved must be the type most recently stored
- Member access to unions is the same as for structures (‘`.`’ and ‘`->`’)
- Unions can be nested inside structures, and vice versa

Bit fields

- Bit fields allow low-level access to individual bits of a word
- Useful when memory is limited, or to interact with hardware
- A bit field is specified inside a struct by appending a declaration with a colon (`:`) and number of bits; for example: `struct fields { int f1 : 2; int f2 : 3;};`
- Members are accessed in the same way as for structs and unions
- A bit field member does not have an address (no `&` operator)
- Lots of details about bit fields are implementation specific:
  - word boundary overlap & alignment, assignment direction, etc.

Example (adapted from K&R)

```
struct { /* a compiler symbol table */
  char *name;
  struct {
   unsigned int is_keyword : 1;
   unsigned int is_extern : 1;
   unsigned int is_static : 1;
   ...
   } flags;
  int utype;
  union {
   int ival; /* accessed as symtab[i].u.ival */
   float fval;
   char *sval;
   } u;
} symtab[NSYM];
```

Exercises

1. If `p` is a pointer, what does `p[-2]` mean? When is this legal?
2. Write a string search function with a declaration of `char *strfind(const char *s, const char *f);` which returns a pointer to first occurrence of `s` in `f` (and `NULL` otherwise)
3. If `p` is a pointer to a structure, write some C code which uses all the following code snippets: "`++p->i`", "`p++->i`", "`*p->i`", "`*p->i++`", "`(*p->i)++`" and "`*p++->i`"; describe the action of each code snippet
4. Write a program `calc` which evaluates a reverse Polish expression given on the command line; for example
   ```
   $ calc 2 3 4 + *
   ```
   should print `14` (K&R Exercise 5-10)