Hacking in C

Pointers

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Allocation of multiple variables

Consider the program

```
main(){
  char x;
  int i;
  short s;
  char y;
  ....
}
```

What will the layout of this data in memory be?

Assuming 4-byte ints, 2-byte shorts, and little endian architecture

Printing addresses where data is located

We can use & to see where data is located

```
char x; int i; short s; char y;

printf("x is allocated at %p \n", &x);
printf("i is allocated at %p \n", &i);
printf("s is allocated at %p \n", &s);
printf("y is allocated at %p \n", &y);
    // Here %p is used to print pointer values
```

Compiling with or without -O2 will reveal different alignment strategies

Data alignment

Memory as a sequence of bytes

...		**x**	$\mathbf{i}_0$	$\mathbf{i}_1$	$\mathbf{i}_2$	$\mathbf{i}_3$	$\mathbf{s}_0$	$\mathbf{s}_1$	**y**			...

But on a 32-bit machine, the memory is a sequence of 4-byte words

x	$\mathbf{i}_0$	$\mathbf{i}_1$	$\mathbf{i}_2$
$\mathbf{i}_3$	$\mathbf{s}_0$	$\mathbf{s}_1$	**y**
			...

Now the data elements are not nicely aligned with the words,
which will make execution slow, since CPU instructions act on words.

Data alignment

Different allocations, with better/worse alignment

x	$\mathbf{i}_0$	$\mathbf{i}_1$	$\mathbf{i}_2$
$\mathbf{i}_3$	$\mathbf{s}_0$	$\mathbf{s}_1$	**y**
			...

Lousy alignment, but
uses minimal memory

Data alignment

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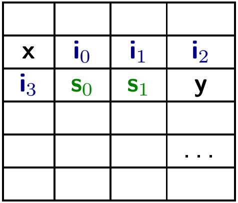

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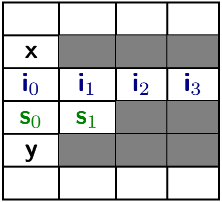

Optimal alignment, but wastes memory

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$\mathbf{x}$	$\mathbf{i}_0$	$\mathbf{i}_1$	$\mathbf{i}_2$
$\mathbf{i}_3$	$\mathbf{s}_0$	$\mathbf{s}_1$	$\mathbf{y}$
			...

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$\mathbf{x}$			
$\mathbf{i}_0$	$\mathbf{i}_1$	$\mathbf{i}_2$	$\mathbf{i}_3$
$\mathbf{s}_0$	$\mathbf{s}_1$		
$\mathbf{y}$			

Optimal alignment, but wastes memory

$\mathbf{s}_0$	$\mathbf{s}_1$	$\mathbf{x}$	$\mathbf{y}$
$\mathbf{i}_0$	$\mathbf{i}_1$	$\mathbf{i}_2$	$\mathbf{i}_3$
			...

Possible compromise

Data alignment

Compilers may introduce padding or change the order of data in memory to improve alignment.

There are trade-offs here between speed and memory usage.

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Most C compilers can provide many optional optimizations. E.g., use

```
man gcc
```

to check out the many optimization options of gcc.

Arrays

Arrays

An array contains a collection of data elements with the same type.
The size is constant.

```
int test_array[10];
int a[] = {30,20};
test_array[0] = a[1];

printf("oops %d \n", a[2]); //will compile & run
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Array bounds are **not** checked.
Anything may happen when accessing outside array bounds. The program may crash, usually with a segmentation fault (segfault).

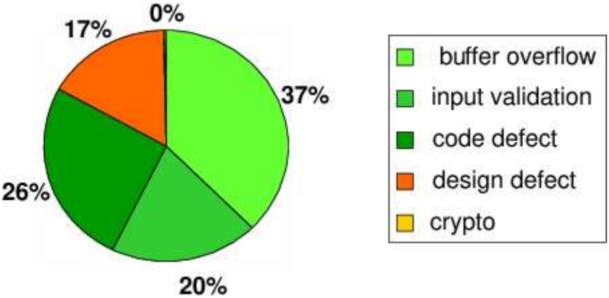
Array bounds checking

The historic decision **not** to check array bounds is responsible for in the order of 50% of all the security vulnerabilities in software, in the form of so-called buffer overflow attacks.

Other languages took a different (more sensible?) choice here. E.g. ALGOL60, defined in 1960, already included array bound checks.

Typical software security vulnerabilities

Security bugs found in Microsoft's first security bug fix month (2002)



Here *buffer overflows* are platform-specific.
Some of the *code defects* and *input validation* problems might also be.
Crypto problems are much more rare, but can be of very high impact.

Array bounds checking

Tony Hoare in Turing Award
speech on the design principles of ALGOL 60

"The first principle was *security*: . . . A consequence of this principle is that every subscript was checked at run time against both the upper and the lower declared bounds of the array. Many years later we asked our customers whether they wished us to provide an option to switch off these checks in the interests of efficiency. Unanimously, they urged us not to – they knew how frequently subscript errors occur on production runs where failure to detect them could be disastrous. I note with fear and horror that even in 1980, language designers and users have not learned this lesson. In any respectable branch of engineering, failure to observe such elementary precautions would have long been against the law."

[C.A.R.Hoare, The Emperor's Old Clothes, Communications of the ACM, 1980]

Overrunning arrays

Consider the program

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int y = 7;
char a[2];
int x = 6;
printf("oops %d \n", a[2]);
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What would you expect this program to print?

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There are no guarantees! The program could simply crash, or return any other number, re-format the hard drive, explode, . . .

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By overrunning an array we can try to reverse-engineer the memory layout

Arrays and alignment

The memory space allocated for an array is guaranteed to be contiguous, i.e. `a[1]` is allocated right after `a[0]`.

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E.g. a compiler might allocate 16 bytes rather than 15 bytes for

```
char text[15];
```

Arrays are passed by reference

Arrays are always passed by reference.

For example, given the function

```
void increase_elt(int x[]) {
  x[1] = x[1]+23;
}
```

What is the value of a[1] after executing the following code?

```
int a[2] = {1, 2};
increase_elt(a);
```

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25

Recall call by reference from Imperative Programming

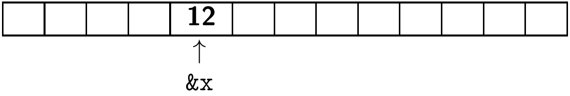
Pointers

Retrieving addresses of *pointers* using &

We can find out *where* some data is allocated using the & operation.
If

```
int x = 12;
```

then `&x` is the memory address where the value of `x` is stored,
aka a pointer to `x`.



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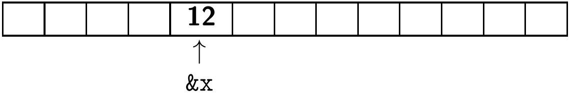

It depends on the underlying architecture how many bytes are needed to represent addresses: 4 on 32-bit machines, 8 on a 64-bit machine.

Declaring pointers

Pointers are typed:
the compiler keeps track of what data type a pointer points to

```
int *p;   // p is a pointer that points to an int
float *f; // f is a pointer that points to a float
```

Creating and dereferencing pointers

Suppose

```
int y, z; int *p; // i.e. p points to an int
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How can we create a pointer to some variable?

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int y, z; int *p; // i.e. p points to an int
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How can we create a pointer to some variable? Using **&**

```
   y = 7
p = &y; // assign the address of y to p
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How can we get the value that a pointer points to?

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How can we get the value that a pointer points to? Using *

```
   y = 7
p = &y; // pointer p now points to y
z = *p; // give z the value of what p points to
```

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int y, z; int *p; // i.e. p points to an int
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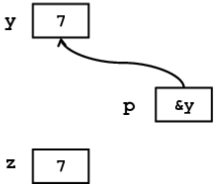
Looking up what a pointer points to, with *, is called dereferencing.

Confused? draw pictures!

```
int y = 7;
int *p = &y; // pointer p now points to cell y
int z = *p;  // give z the value of what p points to
```



Pointer quiz

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int y = 2;
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3. Multiplication of numeric values

   Some legal C code can get confusing, e.g.

```
z = 3 * *p
```

Style debate: `int* p` or `int *p`?

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Downside of writing `int*`

```
int* x, y, z;
```

declares `x` as a pointer to an `int` and `y` and `z` as `int`...

Still not confused?

```
x = 3;
p1 = &x;
p2 = &p1;
z = **p2 + 1;
```

What will the value of z be?

Still not confused?

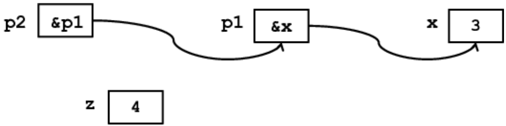
```
x = 3;
p1 = &x;
p2 = &p1;
z = **p2 + 1;
```

What will the value of `z` be?

What should the types of `p1` and `p2` be?

Still not confused? pointers to pointers

```
int x = 3;
int *p1 = &x; // p1 points to an int
int **p2 = &p1; // p2 points to a pointer to an int
int z = **p2 + 1;
```



Pointer test (Hint: example exam question)

```
int y = 2;
int z = 3;
int* p = &y;
int* q = &z;
(*q)++;
*p = *p + *q;
q = q + 1;
printf("y is %d\n", y);
```

What is the value of `y` at the end?

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q = q + 1;
printf("y is %d\n", y);
```

What is the value of `y` at the end?
6
What is the value of `*p` at the end?
6
What is the value of `*q` at the end?
We don't know! `q` points to some memory cell after `z` in the memory

Pointer arithmetic

You can use + and − with pointers.
The semantics depends on the *type of the pointer*:

- adding 1 to a pointer will go to the "next" location, given the size and the data type that it points to.

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The semantics depends on the *type of the pointer*:

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For example, if

```
int *ptr;    char *str;
```

then
`ptr + 2` means "Add `2 * sizeof(int)` to the address in `ptr`"
`str + 2` means "Add 2 to the address in `str`"
(because `sizeof(char)` is 1)

Using pointers as arrays

The way pointer arithmetic works means that a pointer to the head of an array behaves like an array.

Suppose

```
int a[10] = {1,2,3,4,5,6,7,8,9,19};
int *p = (int *) &a; // the address of the head of a
                     // treated as pointer to an int
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```

Now

```
p + 3
```

points to

```
a[3]
```

So we use addition to pointer `p` to move through the array

Pointer arithmetic for strings

What is the output of

```
char *msg = "hello world";
char *t = msg + 6;
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This will print

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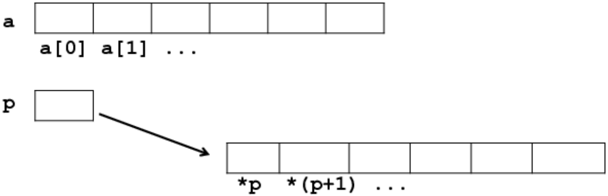
Arrays vs pointers

Arrays and pointers behave similarly, but are very different in memory
Consider

```
int a[]; int *p
```



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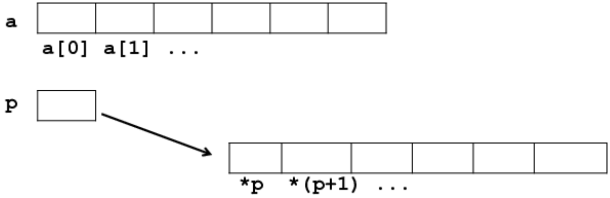

A difference: `a` will always refer to the same array,
whereas `p` can point to different arrays over time

Using pointers as arrays

Suppose

```
int a[10] = {1,2,3,4,5,6,7,8,9,10};
```

Then

```
int sum = 0;
for (int i = 0; i != 10; i++) {
  sum = sum + a[i];
}
```

can also be implemented using pointer arithmetic

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int sum = 0;
for (int *p = (int *)&a; p != &(a[10]); p++) {
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This cast is needed because a is an integer array, so `&a` is a pointer to `int[]`, not pointer to an `int`.
An alternative would be to write `*p = &(a[0])`

Instead of `p != &(a[10])` we could also write `p != ((int *)&a)+10`

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But nobody in their right mind would ☺

A problem with pointers: . . .

```
int i; int j; int *x;
...
// lots of code omitted
i = 5;
j++
// what is the value of i here?
(*x)++;
// what is the value of i here?
```

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```

5

5 or 6, depending on whether `*x` points to `i`

Two pointers are called aliases if they point to the same location

```
int i = 5;
int *x = &i;
int *y = &i;
// x and y are aliases now
(*x)++;
// now i and *y have also changed to 6
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Keeping track of pointers, in the presence of potential aliasing, can be really confusing, and really hard to debug. . .

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with the operations `*` and `&`
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Confusingly, the meaning of addition for pointers depends on their type, as +1 for pointers of type `int *` really means `+sizeof(int)`

The potential of pointers: inspecting raw memory

To inspect a piece of raw memory, we can cast it to a

```
unsigned char *
```

and then inspect the bytes

```
   float f = 3.14;
unsigned char *p = (unsigned char *) &f;
printf("The representation of float %f is", f);
for (int i = 0; i < sizeof(float); i++, p++);) {
printf("%d", *p);
}
printf("\n");
```

Turning pointers into numbers

`intptr_t` defined in `stdint.h` is an integral type that is guaranteed to be wide enough to hold pointers.

```
int *p; // p points to an int
intptr_t i = (intptr_t) p; // the address as a number
p++;
i++;
// Will i and p be the same?
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i++;
// Will i and p be the same?
// No!  i++ increases by 1, p++ with sizeof(int)
```

Turning pointers into numbers

`intptr_t` defined in `stdint.h` is an integral type that is guaranteed to be wide enough to hold pointers.

```
int *p; // p points to an int
intptr_t i = (intptr_t) p; // the address as a number
p++;
i++;
// Will i and p be the same?
// No!  i++ increases by 1, p++ with sizeof(int)
```

There is also an unsigned version of `intptr_t`: `uintptr_t`

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There is a special notation for string literals, between double quotes, where the null terminator is implicit.

As other arrays, we can use both the array type `char[]` and the pointer type `char *` for them.

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1. As for any array, there are no array bounds checks
   so it's the programmer's responsibility not to go outside the array bounds
2. It is also the programmer's responsibility to make sure that the string is properly terminated with a null character.
   If a string lacks its null terminator, e.g. due to problem 1, then standard functions to manipulate strings will go off the rails.

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More precisely, the programmer does not even have to know how strings are represented, and whether null-terminator exists and what they look like: the representation of strings is completely transparant/invisible to the programmer.

Moral of the story: if you can, avoid using standard C strings.
E.g. in C++, use C++ type strings; in C, use safer string libraries.

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```

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Compilers can emit warnings if you change string literals, e.g.

```
gcc -Wwrite-strings
```

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- Their representation
- How these representations can be 'broken', i.e. how we can inspect and manipulate the underlying representation (e.g. with casts)
- Some things that can go wrong
  e.g. due to access outside array bounds or integer under/overflow