Memory, pointers, and C

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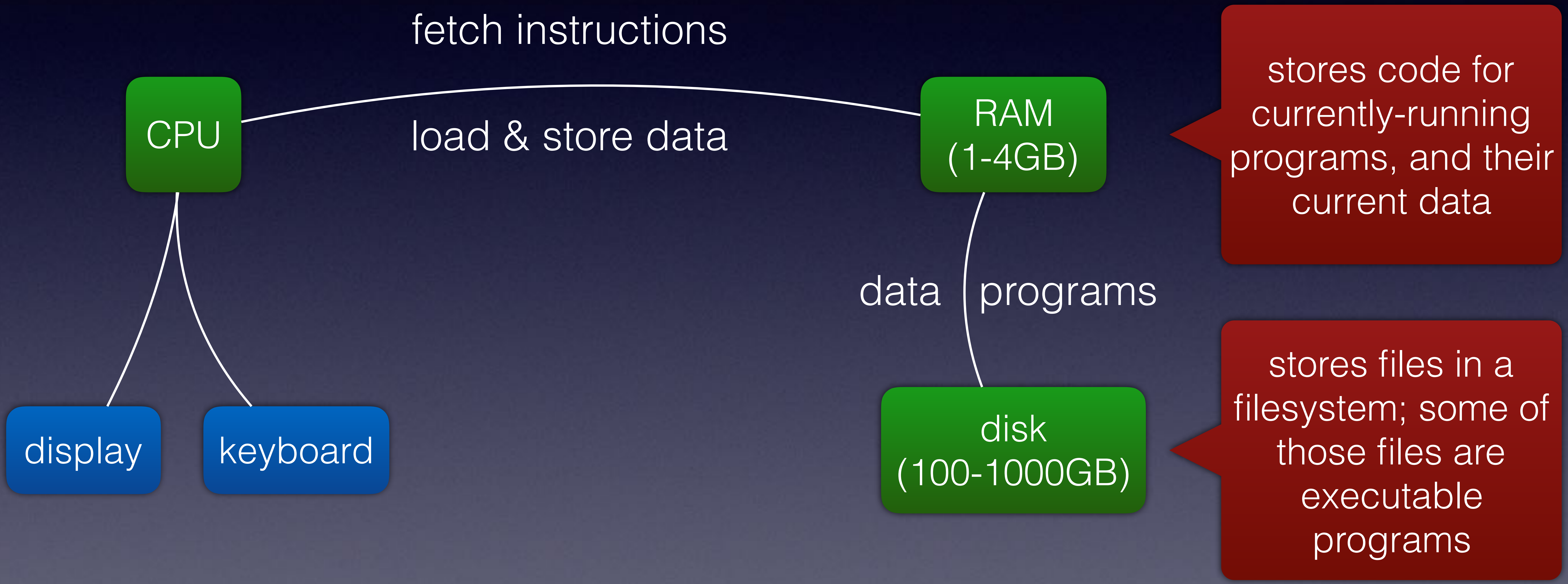
Computer architecture



Memory (RAM)

Every *process* (running program) has its own memory;
every byte in memory has a unique numeric *address.*

today, addresses are 64-bit numbers,
so they can refer to 18 x 10^{18} bytes;
that's 18 exabytes!
example: 0x00007FFD7865430C

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0x means hexadecimal

Characters, and pointers

```
int main()
{
  char c = 'x';                   // a character
  char *p = &c;                   // a pointer to a character
  char **pp = &p;                 // a pointer to a pointer to a character

  printf("c  = '%c'\n", c);
  printf("p  = %12p, *p = '%c'\n", p, *p);
  printf("pp = %12p, *pp = %12p, **pp = '%c'\n", pp, *pp, **pp);

  return 0;
}
```

see `pointer0.c`

pointer0.c – output

```
c  = 'x'
p  = 0x7fffcc62d597, *p = 'x'
pp = 0x7fffcc62d588, *pp = 0x7fffcc62d597, **pp = 'x'
```

*notice that *pp == p*
*and that **pp == *p == c*

because that's how they were initialized

Strings in memory

C has no “string” type; a string is an array of characters ending in a null character (‘\0’); we often refer to a string with a pointer to its first character.

see pointer1.c

pointer1.c

```
char *CS = "Computer Science";

int main()
{
  printf(" CS = %12p, *CS = '%c', CS as string = '%s'\n", CS, *CS, CS);

  for (char *p = CS; *p != '\0'; p++) {
    printf(" p = %12p, *p = '%c'\n", p, *p);
  }

  return 0;
}
```

pointer1.c – output

```
CS = 0x0000400630, *CS = 'C', CS as string = 'Computer Science'
p = 0x0000400630, *p = 'C'
p = 0x0000400631, *p = 'o'
p = 0x0000400632, *p = 'm'
p = 0x0000400633, *p = 'p'
p = 0x0000400634, *p = 'u'
p = 0x0000400635, *p = 't'
p = 0x0000400636, *p = 'e'
p = 0x0000400637, *p = 'r'
p = 0x0000400638, *p = ' '
p = 0x0000400639, *p = 'S'
p = 0x000040063a, *p = 'c'
p = 0x000040063b, *p = 'i'
p = 0x000040063c, *p = 'e'
p = 0x000040063d, *p = 'n'
p = 0x000040063e, *p = 'c'
p = 0x000040063f, *p = 'e'
```

pointer1.c – output

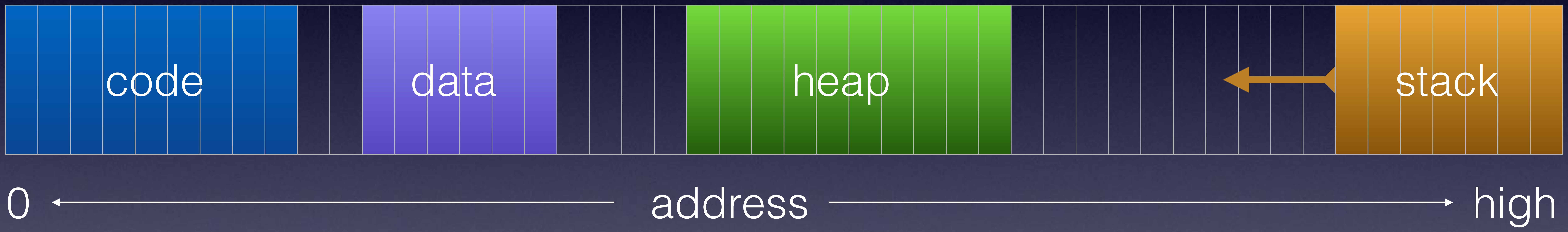
```
CS = 0x0000400630, *CS = 'C', CS as string = 'Computer Science'
p = 0x0000400630, *p = 'C'
p = 0x0000400631, *p = 'o'
p = 0x0000400632, *p = 'm'
p = 0x0000400633, *p = 'p'
p = 0x0000400634, *p = 'u'
p = 0x0000400635, *p = 't'
p = 0x0000400636, *p = 'e'
p = 0x0000400637, *p = 'r'
p = 0x0000400638, *p = ' '
p = 0x0000400639, *p = 'S'
p = 0x000040063a, *p = 'c'
p = 0x000040063b, *p = 'i'
p = 0x000040063c, *p = 'e'
p = 0x000040063d, *p = 'n'
p = 0x000040063e, *p = 'c'
p = 0x000040063f, *p = 'e'
```

notice:

- both **p** and **CS** are pointers
- **p** initially has the same value as **CS**
- (i.e., points to the same address)
- incrementing **p** steps to the next char
- since sizeof(char)=1, address increments by 1
- **p** is an address, ***p** is a character
- printf can print a pointer with **%p**, or interpret that pointer as address of a string with **%s**

Code, data, heap, and stack

Process memory includes compiled **code** (machine instructions), **data** (global variables), **heap** (dynamically allocated), and **stack** (local variables)



Not all addresses will be used; and different compilers and operating systems may lay out the four segments differently

Code memory

All your C code is *compiled* into machine instructions, *linked* with libraries, and laid out within the **code** segment

See example: pointer2.c

Again, the code segment is not necessarily in low memory.

Data memory

All your global variables are laid out in the **data** segment

See example: pointer2.c

Again, the data segment is not necessarily in low memory.

pointer2.c (part 1)

```
const int fifteen = 15;
int main()
{
  // local variables are on the stack
  int x = 2, y = 5;

  // global variables; note they are in low memory addresses
  printf("globals\n");
  printf(" fifteen @ %12p has value %d\n", &fifteen, fifteen);

  // main() is a function, and its code is at an address too!
  printf("main @ %12p\n", main);

  // local variables are on the stack
  printf(" x @ %12p has value %d\n", &x, x);
  printf(" y @ %12p has value %d\n", &y, y);
...
```

Stack memory

Functions' local variables live in the **stack** segment, aka, "on the stack" along with a record of the function-call sequence

The stack starts in high(er) memory addresses, and grows "down" toward lower addresses as function calls are nested

See pointer2.c

pointer2.c – output (part 1)

```
globals – data segment
 fifteen @ 0x0000400750 has value 15
main @ 0x00004005f6 – code segment
 x @ 0x7ffdbf396d3c has value 2 – stack segment
 y @ 0x7ffdbf396d38 has value 5 – stack segment
```

notice that all variables, and functions, have an address;
the name of a function is actually a pointer to that function.
stack variables are in high memory.

pointer2.c (part 2)

```
main...
  // pass x by reference, y by value
  change(&x,y);

  // see whether those changed
  printf("main @ %12p\n", main);
  printf(" x @ %12p has value %d\n", &x, x);
  printf(" y @ %12p has value %d\n", &y, y);
...
}

void change(int *a, int b)
{
  // as above, change() is a function,
  // and its parameters and local variables are on the stack
  printf("change @ %12p\n", change);
  printf(" a @ %12p has value %d at %12p\n", &a, *a, a);
  printf(" b @ %12p has value %d\n", &b, b);
  // attempt to change the values
  *a = 99;
  b = 99;
}
```

Stack memory

Functions' local variables live in the **stack** segment, aka, "on the stack" along with a record of the function-call sequence

The stack starts in high(er) memory addresses, and grows "down" toward lower addresses as function calls are nested

See pointer2.c

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pointer2.c – output (part 2)

```
main @ 0x0000400566 – code segment
 x @ 0x7ffdbf396d3c has value 2
 y @ 0x7ffdbf396d38 has value 5
change @ 0x0000400645 – code segment
 a @ 0x7ffdbf396d18 has value 2 at 0x7ffdbf396d3c
 b @ 0x7ffdbf396d14 has value 5
main @ 0x0000400566
 x @ 0x7ffdbf396d3c has value 99
 y @ 0x7ffdbf396d38 has value 5
```

*notice that the addresses of **a** and **b** are not the same as **x** and **y**.*
*notice that **a** receives the value of **&x**, and thus points to the same address.*
*when **change()** assigns to ***x**, the value of **x** changes – not so for **y**.*

Heap

The **heap** is for dynamically-allocated memory – when you don't know in advance how much space you'll need, or so you can build complex data structures.

C has no language feature like Java's `new` and `delete`.
Instead, a library provides `malloc()` and `free()` functions;
that library manages used and free space within the heap.

pointer3.c

```
int main()
{
  char *hello = "hello world!";
  char buf[15];

  strcpy(buf, "something"); // initialize buf

  // local variables are on the stack
  printf(" hello @ %12p has value '%s', which resides at %12p\n", &hello, hello, hello);
  printf(" buf @ %12p has value '%s', which resides at %12p\n", &buf, buf, buf);

  // malloc allocates space on the heap
  hello = (char *)malloc(10);
  strcpy(hello, "new stuff");
  printf(" now hello @ %12p has value '%s', which resides at %12p\n", &hello, hello, hello);
  // free lets the heap re-use that space
  free(hello);
  printf(" note hello @ %12p still points to %12p\n", &hello, hello);
...
```

Heap

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The heap manager allocates 10 bytes and returns the address, which we save in the pointer variable `hello`.

Heap

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The heap manager allocates 10 bytes and returns the address, which we save in the pointer variable `hello`.

pointer3.c – output

```
hello @ 0x7ffc79c14658 has value 'hello world!', which resides at 0x0000400720
```

notice it is a different address! because it was initialized to point to a constant string.

```
buf @ 0x7ffc79c14640 has value 'something', which resides at 0x7ffc79c14640
```

notice it is the same address! because buf is a character array on the stack.

```
now hello @ 0x7ffc79c14658 has value 'new stuff', which resides at 0x0002278420
```

notice it now points to a new address – inside the heap – provided by malloc()

```
note hello @ 0x7ffc79c14658 still points to 0x0002278420
```

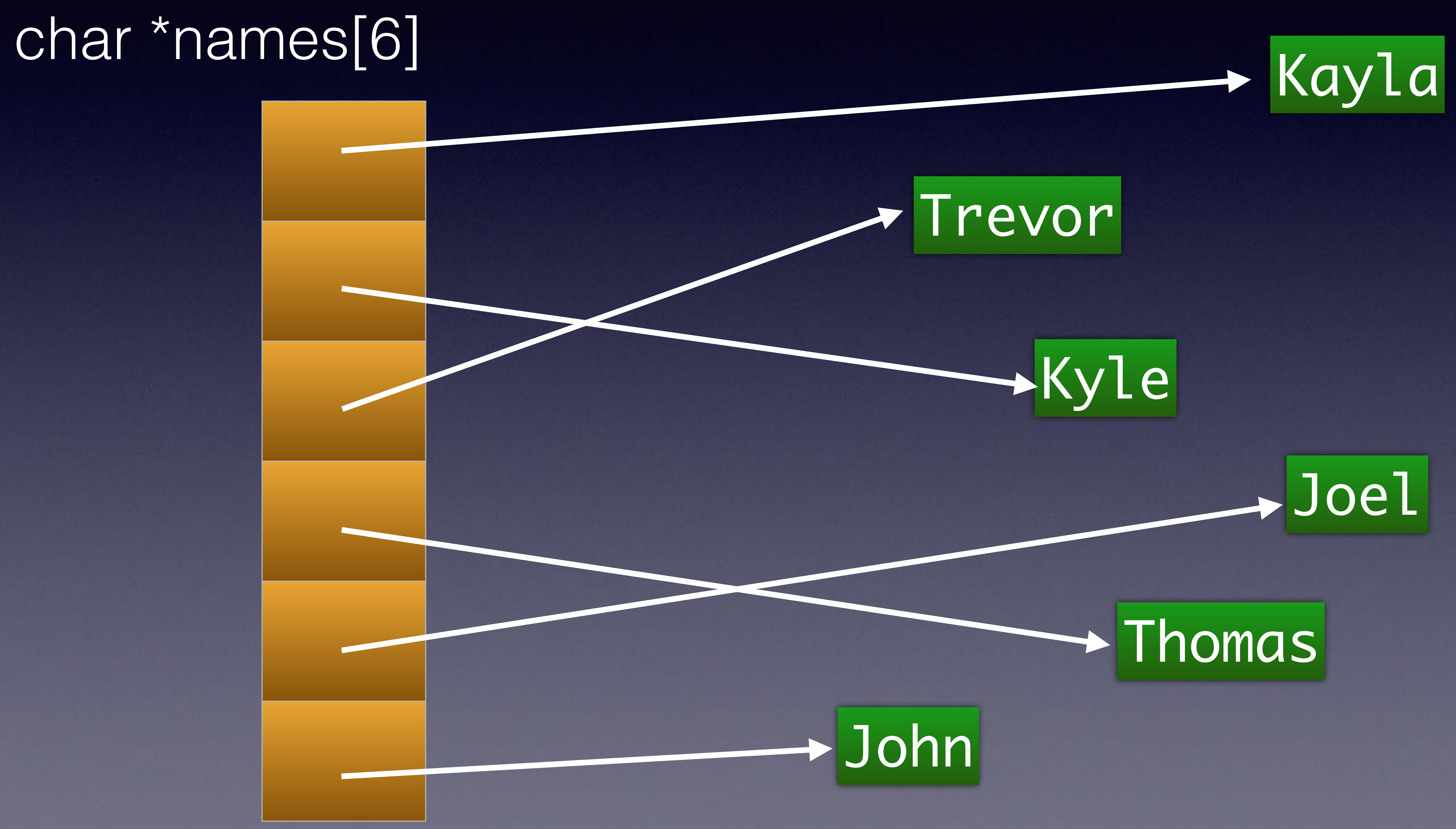
calling free(hello) did not change the pointer, but we should never use that pointer value!

Heap

The **heap** is for dynamically-allocated memory – when you don't know in advance how much space you'll need, or so you can build complex data structures.

After `free(hello)` the heap manager thinks the space is now unallocated and can be used to support future `malloc()` calls. If we keep and re-use the `hello` pointer, bad stuff happens!

Array of strings



see names3.c