CS 106B, Lecture 14
Pointers and Memory Management

Plan for Today

- How does the computer store memory? The stack and the heap
- Memory management and dynamic allocation – powerful tools that allows us to create **linked data structures** (next two weeks of the course)
  - Pointers and memory addresses – another way to refer to variables
  - Structs – an easy way to group variables together
  - Arrays

Structs

- Like a class, but simpler
  - Collection of variables together
  - Easy way to create more complex types

```
struct Album {
    string title;
    int year;
    string artist_name;
    int artist_age;
    int artist_num_kids;
    string artist_spouse;
};
```

- You can declare a variable of this type and use "." to access fields

```
Album lifeChanges;
lifeChanges.year = 2017;
lifeChanges.title = "Life Changes";
cout << lifeChanges.year << endl;
```

Struct Design

- What's wrong with this struct design?

```
struct Album {
    string title;
    int year;

    string artist_name;
    int artist_age;
    int artist_num_kids;
    string artist_spouse;
};
```

- Style: awkward naming
- How many times do we construct the artist info?

Struct Design

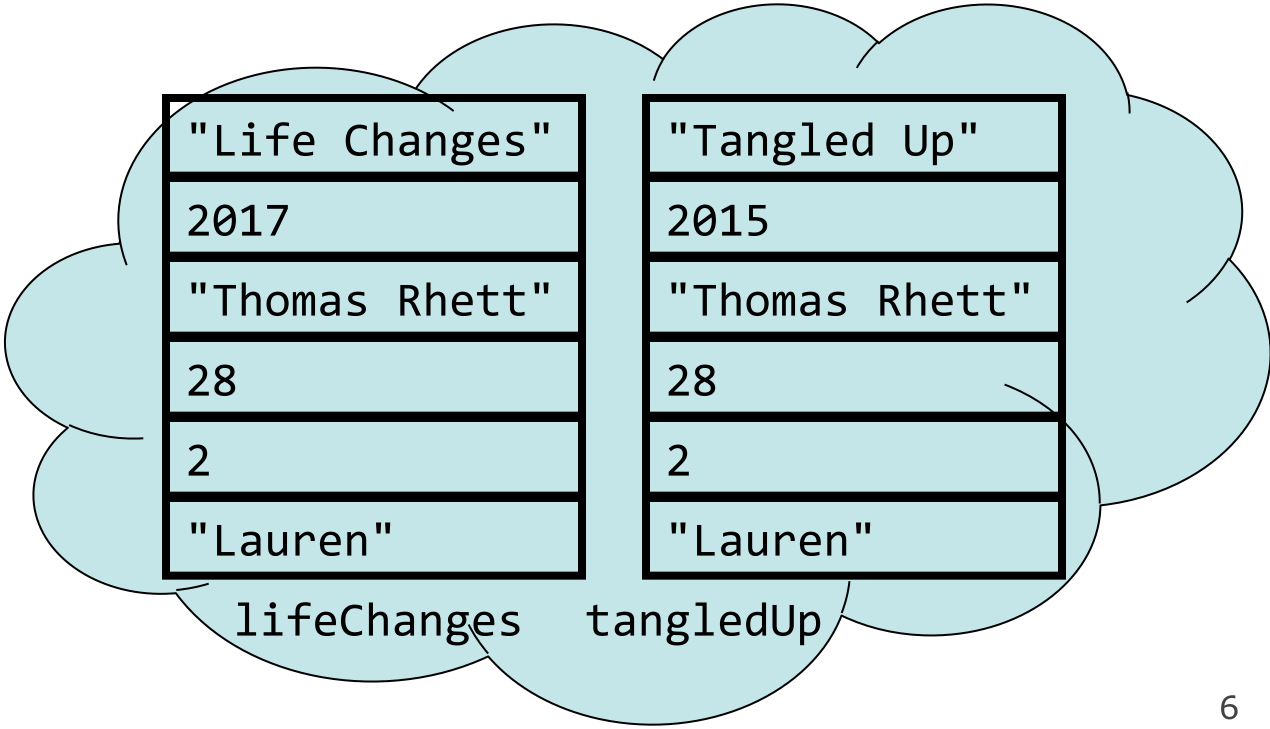
```
Album lifeChanges = {
    "Life Changes",
    2017,
    "Thomas Rhett",
    28,
    2,
    "Lauren"
};

Album tangledUp = {
    "Tangled Up",
    2015,
    "Thomas Rhett",
    28,
    2,
    "Lauren"
};
```

- Redundant code to declare and initialize these albums

Struct Design

```
Album lifeChanges = {
    "Life Changes",
    2017,
    "Thomas Rhett",
    28,
    2,
    "Lauren"
};

Album tangledUp = {
    "Tangled Up",
    2015,
    "Thomas Rhett",
    28,
    2,
    "Lauren"
};
```

- Redundant code to declare and initialize these albums
- Redundant to store too
  - Imagine if the artist info took up a lot of space



Fixing Redundancy

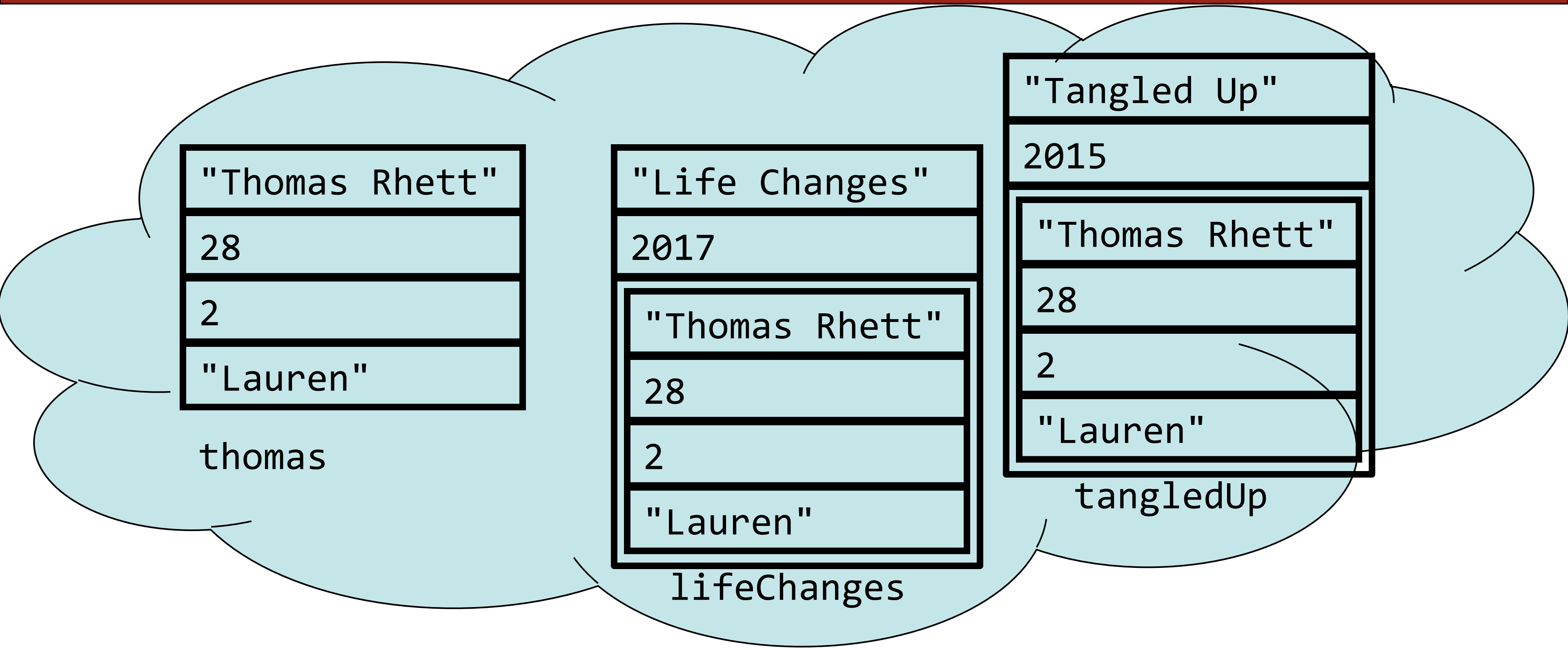
```
struct Album {
    string title;
    int year;

    string artist_name;
    int artist_age;
    int artist_num_kids;
    string artist_spouse;
};
```

Should probably be another struct?

The Artist Struct

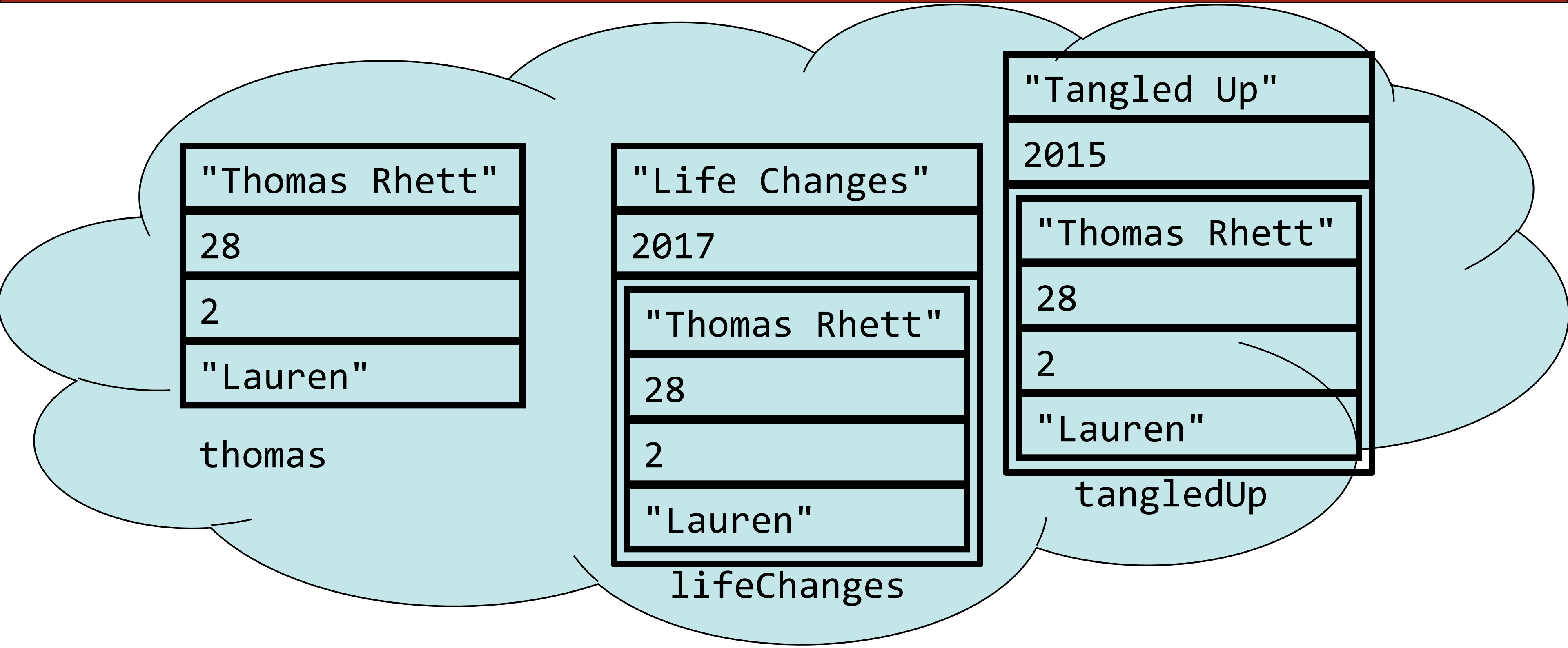
```
struct Album {
    string title;
    int year;

    Artist artist;
};

struct Artist {
    string name;
    int age;
    int num_kids;
    string spouse;
};

Artist thomas = {"Thomas Rhett", 28, 2, "Lauren"};

Album lifeChanges = {"Life Changes", 2017, thomas};
Album tangledUp = {"Tangled Up", 2015, thomas};
```

Artist In Memory



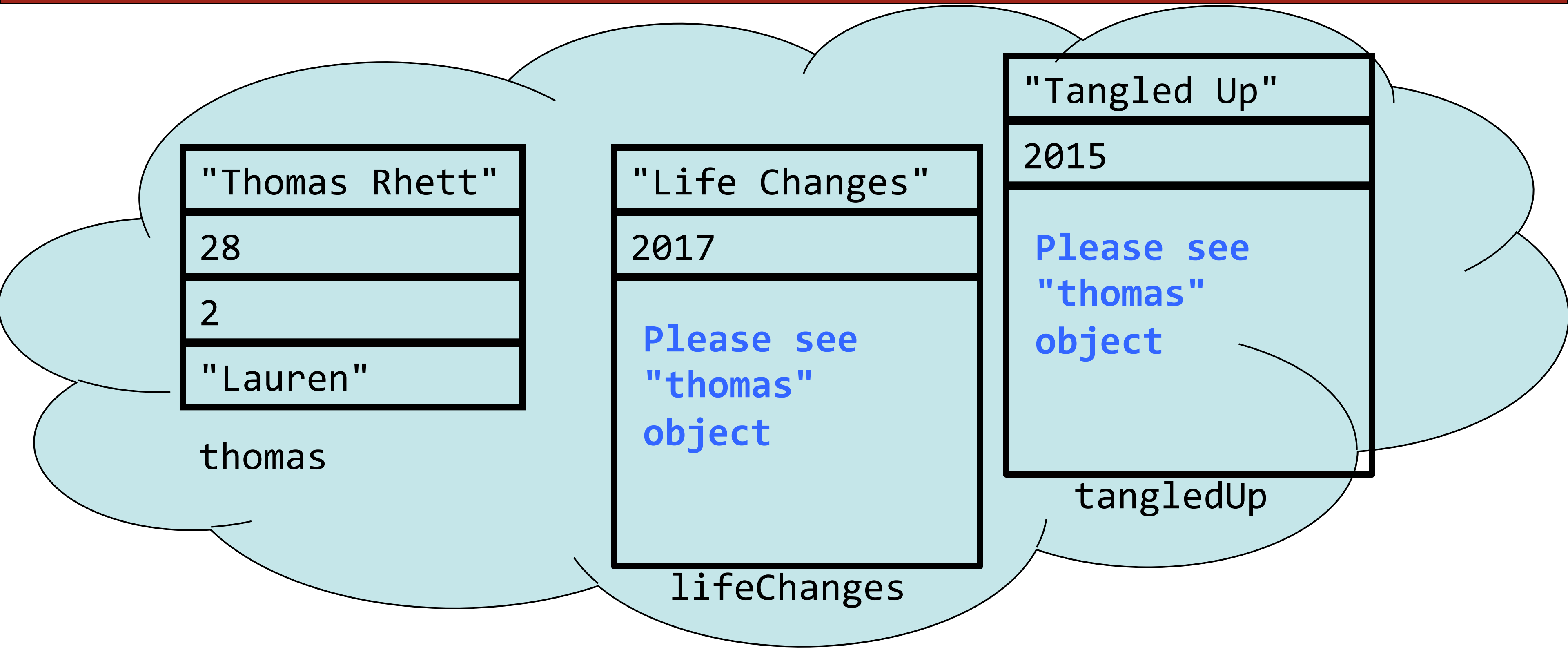

```
Artist thomas = {"Thomas Rhett", 28, 2, "Lauren"};

Album lifeChanges = {"Life Changes", 2017, thomas};
Album tangledUp = {"Tangled Up", 2015, thomas};
```

Artful Redundancy




```
Artist thomas = {"Thomas Rhett", 28, 2, "Lauren"};

Album lifeChanges = {"Life Changes", 2017, thomas};
Album tangledUp = {"Tangled Up", 2015, thomas};

thomas.num_kids++; // what happens?
```

What we want



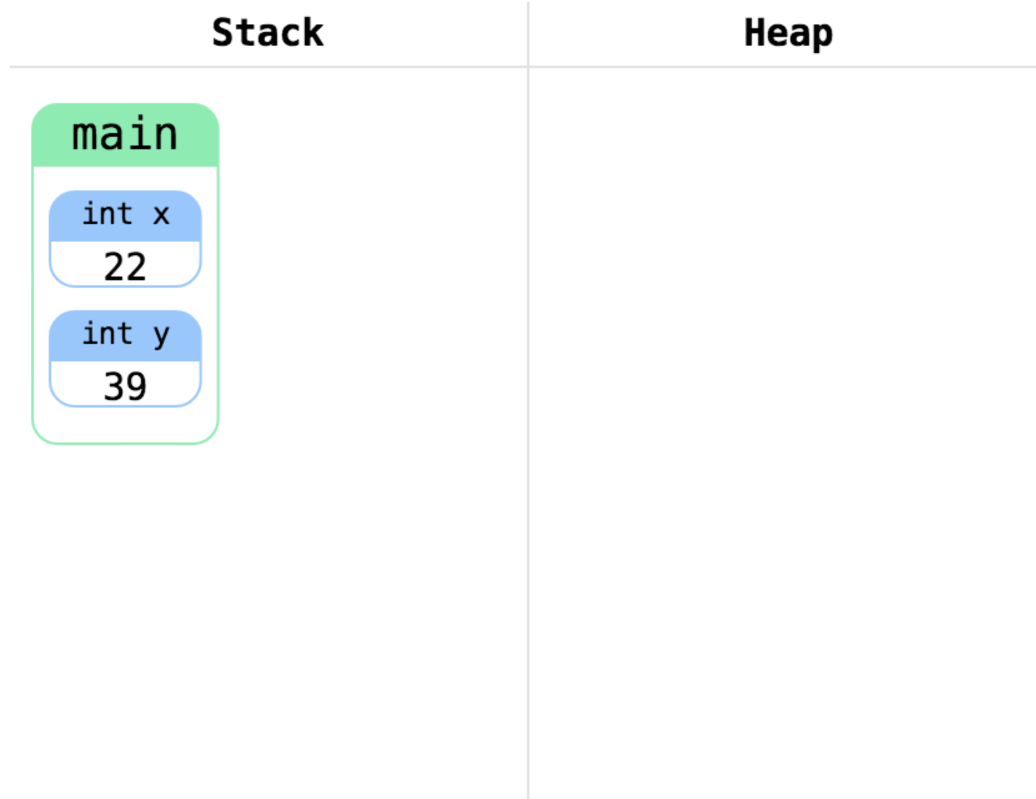
- The artist field should **point to** or **refer to** the "thomas" data structure instead of storing it
  - if only we could just tell the computer **where in memory** to look for the thomas structure....
- In C++ - **pointers!**

Computer Memory

- Creating a variable **allocates** memory (spot for the variable in the computer)
  - We number the spots in memory (just like houses) with a **memory address**
    - Can think of a computer's memory as a giant **array**, spread between stack and heap
- Stack
  - stores all the local variables, parameters, etc.
  - manages memory automatically
- Heap
  - memory that **you** manage
  - Advantage: you get to decide when the memory is freed (instead of it always disappearing at the end of a function)
  - Disadvantage: you need to manage the memory yourself

Code Trace

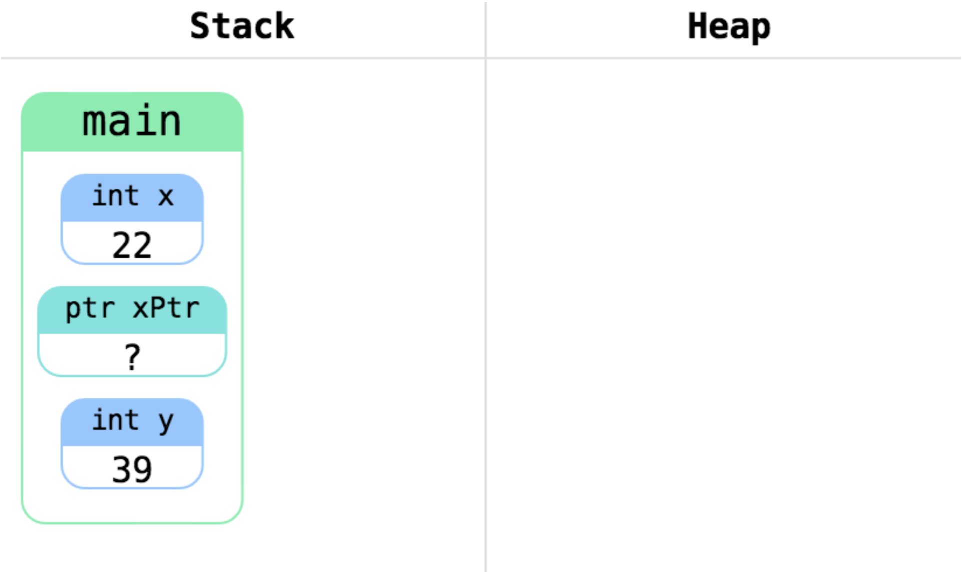
```
int x = 22;
int y = 39;
```



Creating variables on the stack:
These lines declare and initialize two variables on the stack

Code Trace

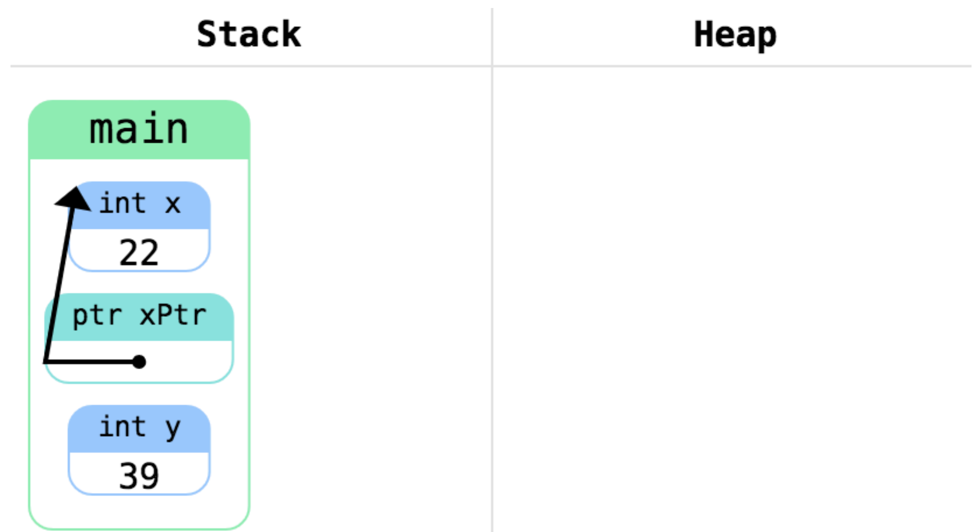
```
int x = 22;
int y = 39;
int *xPtr;
```



Creating a pointer:
xPtr will store a reference to an int
We say that a pointer "points to" a place in memory, because it stores a memory address
Like all local variables, xPtr is on the stack
The type before the asterisk is the type the pointer points to

Code Trace

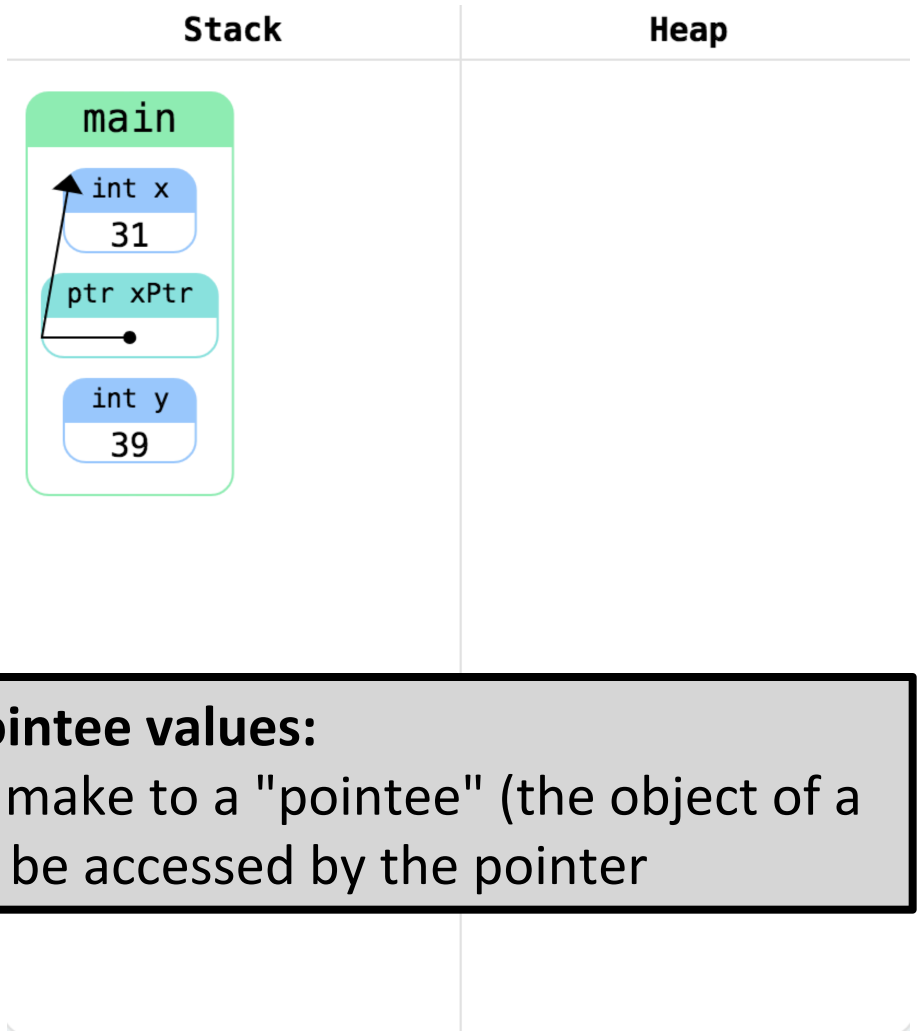
```
int x = 22;
int y = 39;
int *xPtr;
xPtr = &x;
```



Initializing a pointer:
xPtr now points to the variable x (the pointee)
The & operator gets the memory address of a variable, which is now stored in xPtr

Code Trace

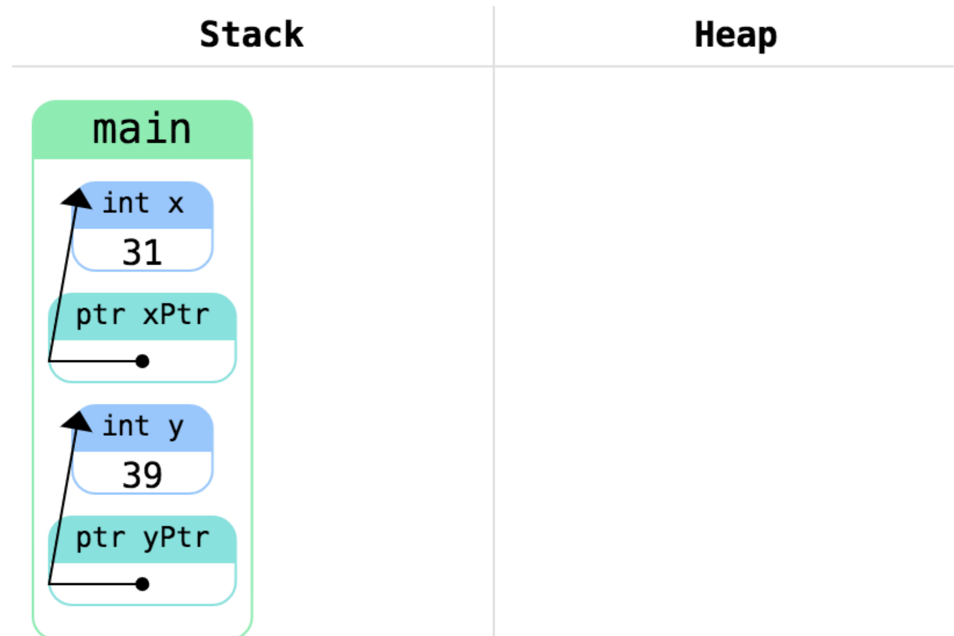
```
int x = 22;
int y = 39;
int *xPtr;
xPtr = &x;
x += 9;
```



Changing pointee values:
Changes we make to a "pointee" (the object of a pointer) can be accessed by the pointer

Code Trace

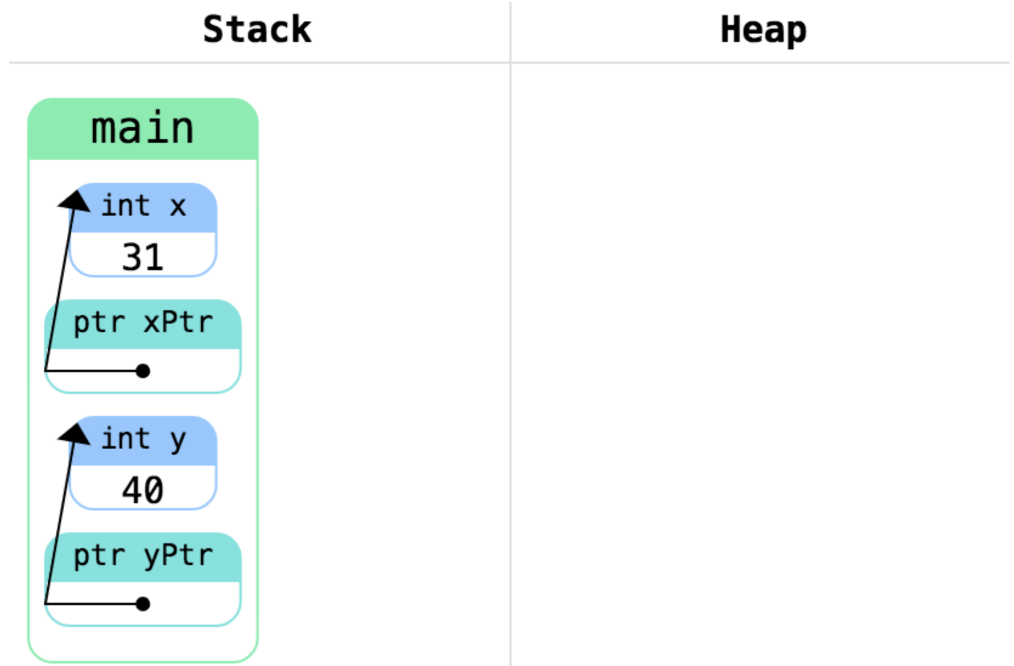
```
int x = 22;
int y = 39;
int *xPtr;
xPtr = &x;
x += 9;
int *yPtr = &y;
```



Creating a pointer:
Here we create another pointer, this time pointing to the variable y

Code Trace

```
int x = 22;
int y = 39;
int *xPtr;
xPtr = &x;
x += 9;
int *yPtr = &y;
(*yPtr)++;
```



Accessing Pointees:
We can **dereference** a pointer using the * operator
In this example, we add 1 to the value that yPtr points to

The Stack

- A **pointer** is a special type that stores the address for a variable
  - Needs to be declared with an asterisk (meaning pointer) to the type stored in the block

```
int *pointer; // stores the memory address for an int
string *strPointer; // stores memory address for a string
```

- To create a variable on the stack, we just declare it (all variables you've created in this class so far have been on the stack)

```
Album lifeChanges;
```

  - We can get the memory address using an & (address operator)

```
Album *pointer = &lifeChanges;
```

Pointer Syntax Recap

- Declaring a pointer

```
type* name;
```

- Dereferencing a pointer
  - Gets the variable from the address (the variable the pointer points to)
  - Also uses the *

```
type variable = *pointer;
```

  - To access a field in a pointer to a struct:

```
int year = (*album).year;
```

  - Alternative syntax uses -> instead:

```
int year = album->year;
```

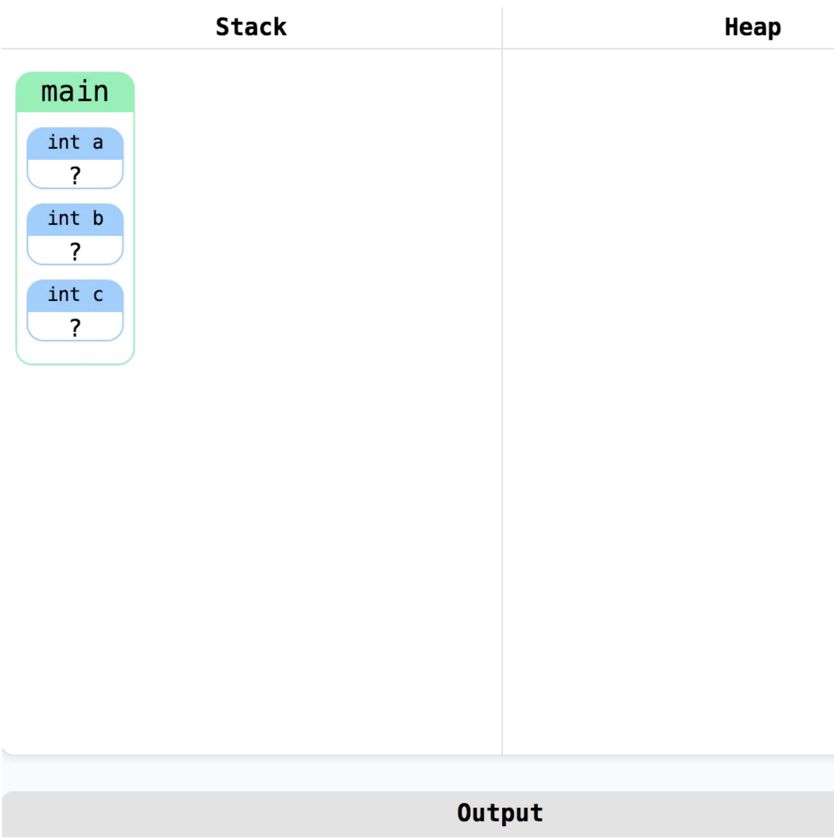
Pointer mystery

- As parameters, pointers work similarly to references.

```
void mystery(int a, int& b, int* c) {
    a++;
    (*c)--;
    b += *c;
    cout << a << " " << b << " " << *c << " " << endl;
}

int main() {
    int a = 4;
    int b = 8;
    int c = -3;

    cout << a << " " << b << " " << c << " " << endl;
    mystery(c, a, &b);
    cout << a << " " << b << " " << c << " " << endl;
    return 0;
}
```

Pointer mystery

```
void mystery(int a, int& b, int* c) {
    a++;
    (*c)--;
    b += *c;
    cout << a << " " << b << " " <<
  *c << " " << endl;
}

int main() {
    int a = 4;
    int b = 8;
    int c = -3;

    cout << a << " " << b << " " << c
  << " " << endl;
    mystery(c, a, &b);
    cout << a << " " << b << " " << c
  << " " << endl;
    return 0;
}
```

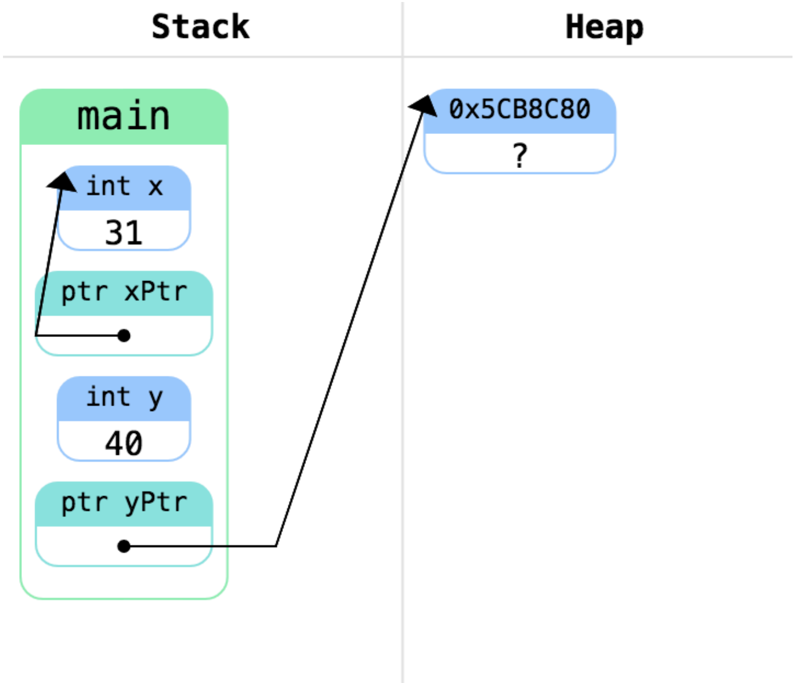


Announcements

- Grades for assignment 2 should be released; assignment 4 (backtracking) released later today
- Exam logistics
  - Midterm review session in one week, from 7:00-8:30PM, in Gates B01, led by SL Peter
  - Midterm is on Wednesday, July 25, from 7:00-9:00PM in Hewlett 200
  - Midterm info (list of topics covered and study tips) online: https://web.stanford.edu/class/cs106b/exams/midterm.html
  - Practice exam is posted – gives you an idea of what to expect, not necessarily going to be identical
  - Complete assignment 4 before the midterm – backtracking will be tested

Code Trace Continued

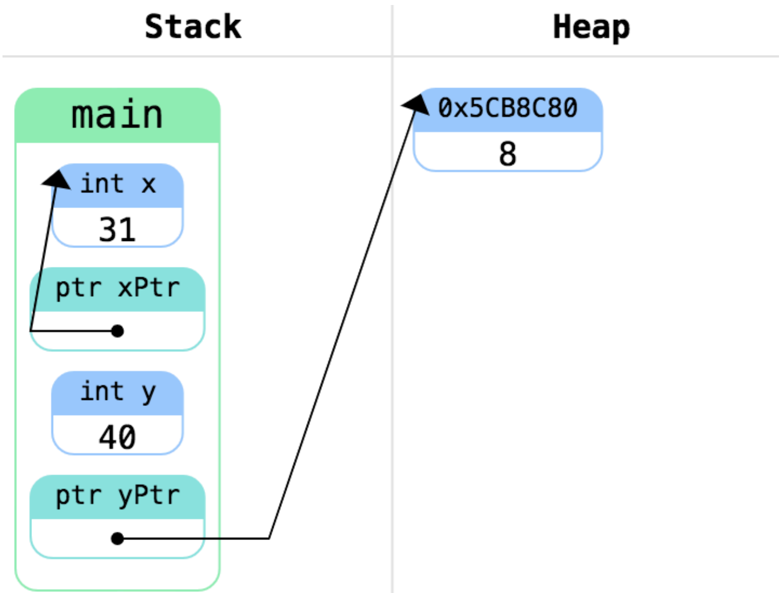
```
int x = 22;
int y = 39;
int *xPtr;
xPtr = &x;
x += 9;
int *yPtr = &y;
(*yPtr)++;
yPtr = new int;
```



Creating memory on the heap:
Only way to create memory on the heap is with **new**
Asks the computer for more memory
You're responsible for unallocating (freeing) the memory

Code Trace Continued

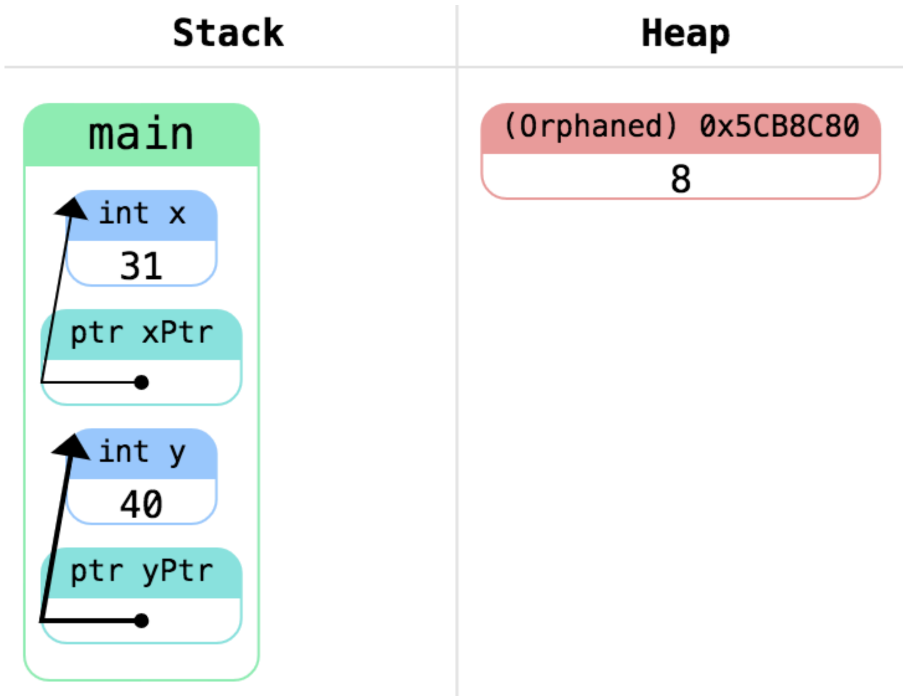
```
int x = 22;
int y = 39;
int *xPtr;
xPtr = &x;
x += 9;
int *yPtr = &y;
(*yPtr)++;
yPtr = new int;
*yPtr = 8;
```



Accessing Heap Memory:
Same as with pointers to memory on the stack
Use the * to dereference

Code Trace Continued

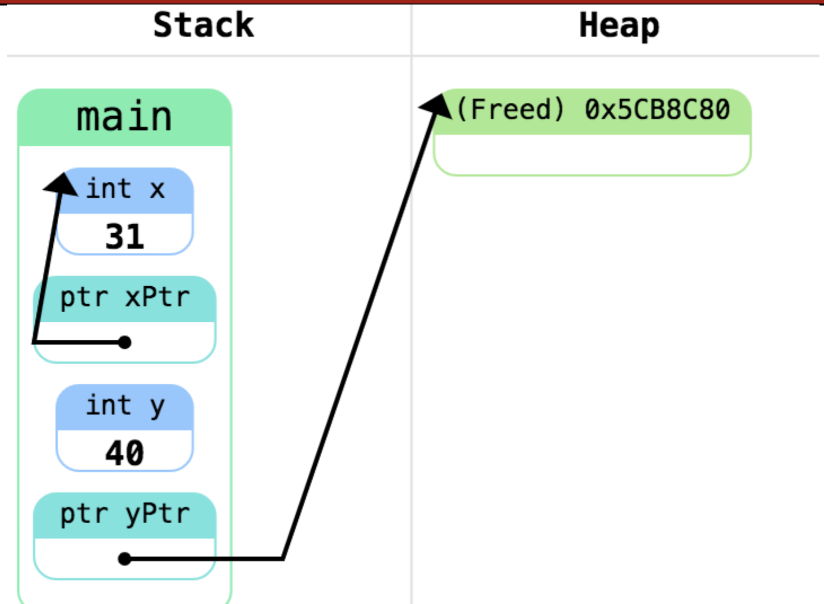
```
int x = 22;
int y = 39;
int *xPtr;
xPtr = &x;
x += 9;
int *yPtr = &y;
(*yPtr)++;
yPtr = new int;
*yPtr = 8;
yPtr = &y;
```



Orphaned Memory:
If we lose all the pointers to a block of heap-allocated memory, we say it's "orphaned"
There's no way to access it or tell the computer we're done using it – that slows the computer down

Code Trace Continued

```
int x = 22;
int y = 39;
int *xPtr;
xPtr = &x;
x += 9;
int *yPtr = &y;
(*yPtr)++;
yPtr = new int;
*yPtr = 8;
delete yPtr;
```



Freeing Memory:

To tell the computer we don't need the heap memory anymore, we call **delete**

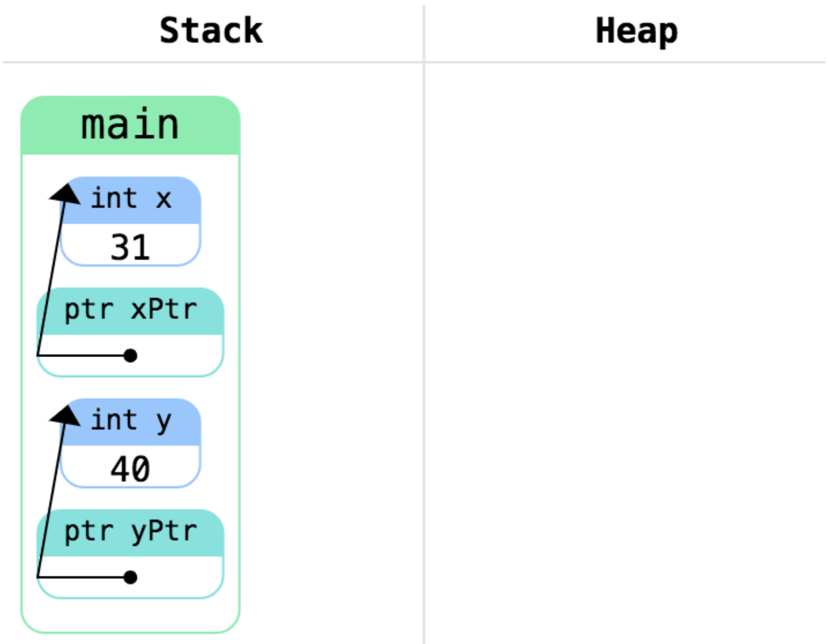
Every **new** needs a **delete**

If we dereference freed memory, unpredictable behavior (crash!)

Stack memory is automatically freed when the function ends

Code Trace Continued

```
int x = 22;
int y = 39;
int *xPtr;
xPtr = &x;
x += 9;
int *yPtr = &y;
(*yPtr)++;
yPtr = new int;
*yPtr = 8;
delete yPtr;
yPtr = &y;
```



Reassigning Pointers:
After freeing the memory, we can reassign the pointer without leaking memory
Calling delete changed the pointee not the pointer

Pointers and the Heap

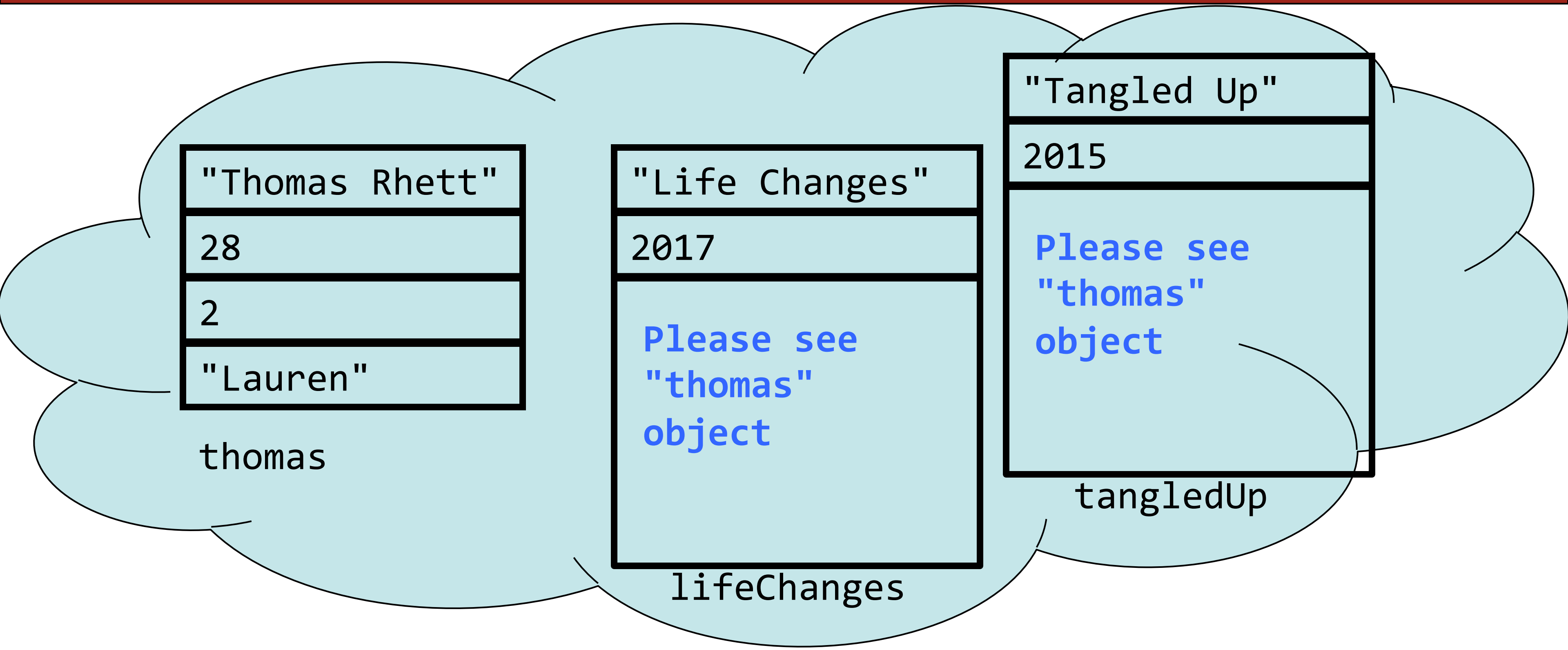
- Creating a variable on the heap uses the new keyword
  - Allocates memory on the heap and returns the location to store in the pointer
  - Note: the pointer itself is still a local variable (it has a name)

```
Album* lifeChanges = new Album;
```

- Freeing memory – everything created must be destroyed
  - The Album will exist even if lifeChanges goes out of scope or changes values
    - "orphaning memory" – the Album isn't pointed to by anything anymore
    - When memory is orphaned, we say the program has a **memory leak**
    - Can cause your program to slow down
  - To free the Album, use the `delete` keyword **on the pointer**

```
delete lifeChanges; // lifeChanges can be reassigned now
```

Album improvements

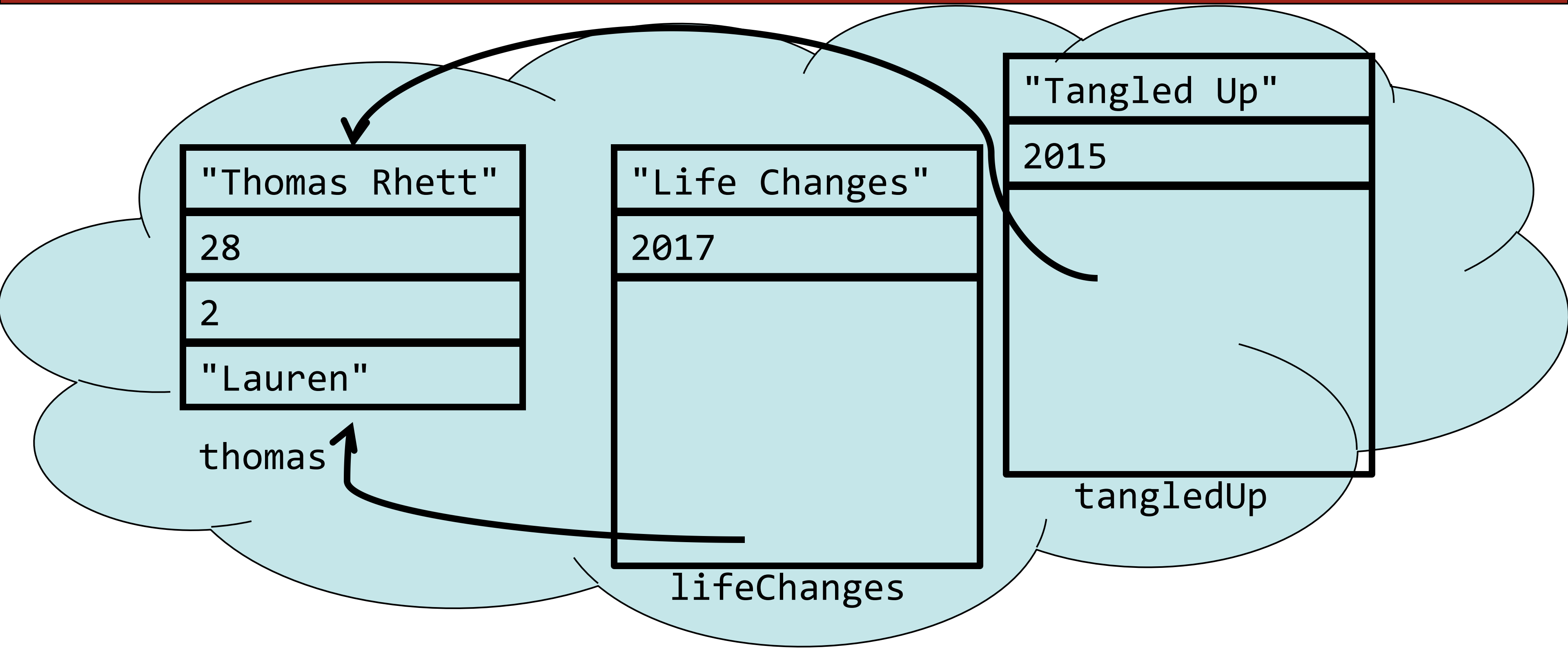


– What should the Album struct look like?

The Album Struct Redux

```
struct Album {
    string title;
    int year;

    Artist *artist;
};

struct Artist {
    string name;
    int age;
    int num_kids;
    string spouse;
};

Artist *thomas = new Artist{"Thomas Rhett", 28, 2, "Lauren"};

Album *lifeChanges = new Album{"Life Changes", 2017, thomas};
Album *tangledUp = new Album{"Tangled Up", 2015, thomas};
```

Album improvements




```
Artist *thomas = new Artist{"Thomas Rhett", 28, 2, "Lauren"};
Album *lifeChanges = new Album{"Life Changes", 2017, thomas};
Album *tangledUp = new Album{"Tangled Up", 2015, thomas};
cout << tangledUp->artist->spouse << endl; // "Lauren"
// later in the code, maybe in a different function
delete thomas; delete tangledUp; delete lifeChanges;
```

Null/garbage pointers

- **null pointer**: Memory address 0; "points to nothing".
- **uninitialized pointer**: points to a random address.
  - If you dereference these, program will probably crash.

```
int x = 42;
int* p1 = nullptr;      // stores 0
int* p2;                // uninitialized
cout <<  p1 << endl;    // 0
cout << *p1 << endl;    // KABOOM
cout << *p2 << endl;    // KABOOM

// testing for nullness
if (p1 == nullptr) {...}  // true
if (p1)            {...}  // false
if (!p1)           {...}  // true
```

0x7f8e20	x	42
0x7f8e24	p1	0x0
0x7f8e28	p2	0x??????

More Complicated Trace

```
struct Album {
    string title;
    int year;
    string artist;
};

int main() {
  Album *myLibrary = makeLibrary();
  // do something with library
  delete[] myLibrary;
  return 0;
}

Album *makeLibrary() {
  Album* library = new Album[3];
  library[0] = {"Life Changes", 2017, "Thomas Rhett"};
  library[1] = {"Montevallo", 2014, "Sam Hunt"};
  library[2] = {"Not as Legit as Git", 2018, "Anand"};
  return library;
}
```

Heap allocated memory persists: One of the advantages of heap-allocated memory is it persists after the stack frame returns

More Complicated Trace

```
struct Album {
    string title;
    int year;
    string artist;
};

int main() {
  Album *myLibrary = makeLibrary();
  // do something with library
  delete[] myLibrary;
  return 0;
}

Album *makeLibrary() {
  Album* library = new Album[3];
  library[0] = {"Life Changes", 2017, "Thomas Rhett"};
  library[1] = {"Montevallo", 2014, "Sam Hunt"};
  library[2] = {"Not as Legit as Git", 2018, "Anand"};
  return library;
}
```

Arrays:
This line creates an array of size 3 on the heap
Arrays are fixed-size – you can't make them bigger or smaller
That block is pointed to by the variable album

More Complicated Trace

```
struct Album {
    string title;
    int year;
    string artist;
};

int main() {
  Album *myLibrary = makeLibrary();
  // do something with library
  delete[] myLibrary;
  return 0;
}

Album *makeLibrary() {
  Album* library = new Album[3];
  library[0] = {"Life Changes", 2017, "Thomas Rhett"};
  library[1] = {"Montevallo", 2014, "Sam Hunt"};
  library[2] = {"Not as Legit as Git", 2018, "Anand"};
  return library;
}
```

Array Elements:
Arrays are originally uninitialized
You can access each element by index (just like Vector)
Returns the actual element **NOT a pointer**

More Complicated Trace

```
struct Album {
    string title;
    int year;
    string artist;
};

int main() {
  Album *myLibrary = makeLibrary();
  // do something with library
  delete[] myLibrary;
  return 0;
}

Album *makeLibrary() {
  Album* library = new Album[3];
  library[0] = {"Life Changes", 2017, "Thomas Rhett"};
  library[1] = {"Montevallo", 2014, "Sam Hunt"};
  library[2] = {"Not as Legit as Git", 2018, "Anand"};
  return library;
}
```

Deleting Arrays:
Just as **new** used the square brackets to create the array, you must call **delete** with square brackets to free the array's memory

More Complicated Trace

```
struct Album {
    string title;
    int year;
    string artist;
};

int main() {
  int size;
  Album *myLibrary = makeLibrary(size);
  // do something with library using size
  delete[] myLibrary;
  return 0;
}

Album *makeLibrary(int &size) {
  Album* library = new Album[3];
  library[0] = {"Life Changes", 2017, "Thomas Rhett"};
  library[1] = {"Montevallo", 2014, "Sam Hunt"};
  library[2] = {"Not as Legit as Git", 2018, "Anand"};
  size = 3;
  return library;
}
```

Array Sizes:
Arrays don't have a length field, so we need to store the size in a separate variable

Arrays

- Sometimes, you want a several blocks of memory, not just one block
  - The blocks are stored next to each other
- Solution: array
- Declare an array of **fixed-size**

```
Type* arr = new T[size];
int *arr = new int[7];
```

- Freeing the array (notice the brackets):

```
delete[] arr;
```

- Warnings:
  - Cannot change size (grow or shrink)
  - No bounds-checking – the program will have undefined behavior (crash)
  - Need to store size separately