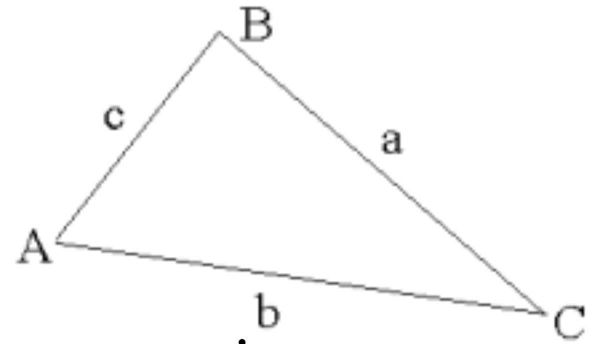
Slides by Andrew DeOrio

EECS 280

Programming and Introductory Data Structures

Abstract Data Types (ADTs)

Review: compound types

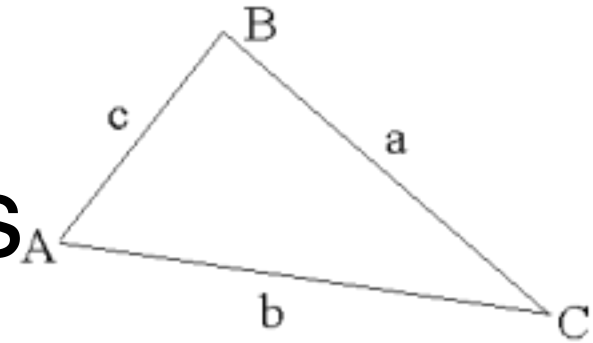


- A compound type "binds together" several other types into one new type
- In C++, we can create a compound type using a `class`

```
class Triangle {
public:
  double a, b, c; //edge lengths
};
```

- `a`, `b`, and `c` are called *member data*

Review: member functions




```
class Triangle {
public:
  double a, b, c; //edge lengths
  double area() { //compute area
    double s = (a+b+c)/2;
    double a = sqrt(s*(s-a)*(s-b)*(s-c));
    return a;
  }
};
```

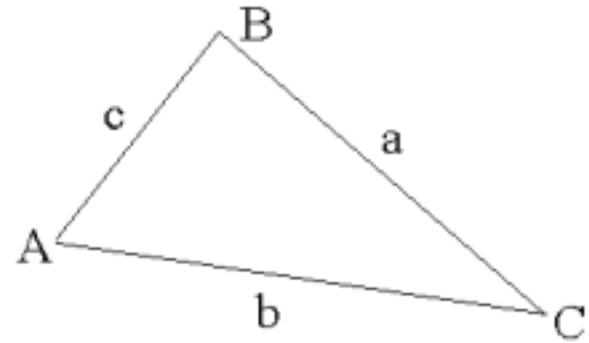
<u>Heron's formula</u>

$$s = \frac{a+b+c}{2}$$

$$area = \sqrt{s(s-a)(s-b)(s-c)}$$

- In addition to data, a `class` can contain *member functions*
- Because member functions are within the same scope as member data, they have access to the member data directly

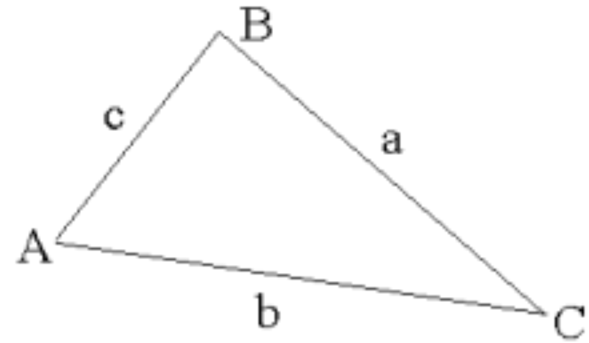
Review: constructors




```
class Triangle {
public:
  double a, b, c; //edge lengths
  double area() {/*...*/}
  Triangle(double a_in, double b_in, double c_in) {
    a = a_in;
    b = b_in;
    c = c_in;
  }
};
```

- Member data can be initialized using a constructor

Review: using classes



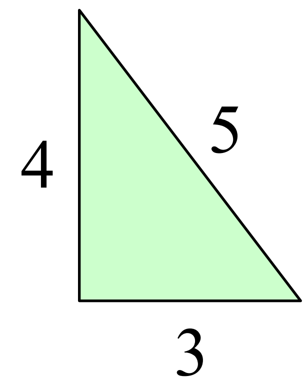

```
class Triangle {/*...*/};
int main() {
  Triangle t(3,4,5);
  cout << t.area() << "\n";
}
```

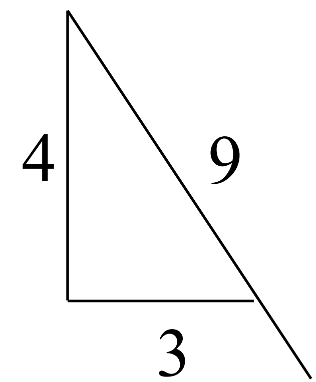
- Users of a class can call member functions

```
$ g++ test.cpp
$ ./a.out
area = 6
```

Review: public and private

```
#include "Triangle.h"
int main() {
  Triangle t(3,4,5);

  // later in the program ...
  t.c = 9;
}
```

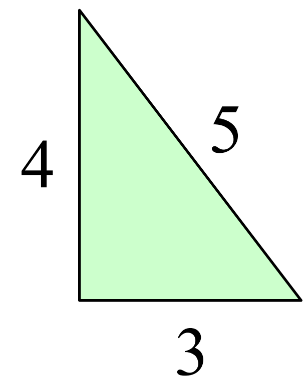


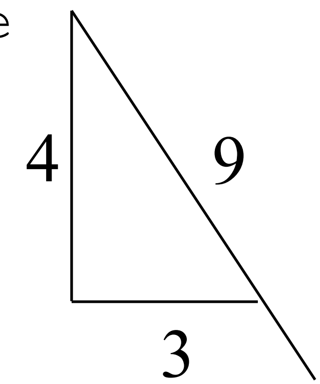


- Problem: `class`'s internal representation of a triangle is no longer a triangle!
- We have violated the *representation invariant*

Review: public and private

```
class Triangle {
  //...
 private:
  //edges are non-negative and form a triangle
  double a, b, c;
};
```





- An ADT's member variables should be `private`
- This is an aspect of *information hiding*

```
int main() {
  Triangle t(3,4,5);
  t.c = 9; //compiler error
}
```

Abstraction in computer programs

- **Procedural abstraction** lets us separate *what* a procedure does from *how* it is implemented
- In C++, we use functions to implement procedural abstraction
- For example:

```
//returns n!, requires that n >= 0
int factorial(int n);
```

```
int factorial (int n) {
  if (n == 0) return 1;
  return n*factorial(n-1);
}
```

```
int factorial(int n) {
  int result = 1;
  while (n != 0) {
    result *= n;
    n -= 1;
  }
  return result;
}
```

Abstraction in computer programs

- **Data abstraction** lets us separate *what* a type is (and what it can do) from *how* the type is implemented

- In C++, we use a `class` to implement data abstraction
  - We can create an Abstract Data Type (ADT) using a `class`

- ADTs let us model complex phenomena
  - More complex than built-in data types like `int`, `double`, etc.

- ADTs make programs easier to maintain and modify
  - You can change the implementation and no users of the type can tell

Creating our ADT

- Let’s build on our triangle compound data type to make it an Abstract Data Type
- We will write an abstract description of values and operations
  - *What* the data type does, but not *how*

`Triangle.h`

- Next, we will implement the ADT
  - *How* the data type works

`Triangle.cpp`

- Finally we will use our new ADT

`Graphics.cpp`

Creating our ADT

- What if we have two programmers?

- Alice and Bob agree on an abstraction

`Triangle.h`

- Alice codes `Triangle.cpp`
  - Implements ADT

`Triangle.cpp`

- Bob codes `Graphics.cpp`
  - Uses ADT

`Graphics.cpp`

Cartoon credit: xkcd.com

Information Hiding and Encapsulation

Information Hiding

- Protect and hide our code from other code that that uses it

Encapsulation

- Keeping data and relevant functions together

Recall our Triangle class

```
class Triangle {
private:
  double a,b,c;
public:
  double area() {
    double s = (a + b + c) / 2;
    return sqrt(s*(s-a)*(s-b)*(s-c));
  }
  Triangle() { a=0, b=0, c=0; }
  Triangle(double a_in, double b_in, double c_in) {
    a=a_in; b=b_in; c=c_in;
  }
};
```

Does `Triangle` provide information hiding? Encapsulation?

Recall our Triangle class

- Information Hiding: **Sort of.**
- We used the `private` keyword to hide member variables from outside users
- **But**, `Triangle`'s function definitions (implementations) are mixed with its function declarations (prototypes)

- Encapsulation: **Yes.**
- `Triangle` uses a class, which ensures that the member functions and member variables stay together.

Recall our Triangle class

- Information Hiding: **Sort of.**
- We used the `private` keyword to hide member variables from outside users
- **But**, `Triangle`'s function definitions (implementations) are mixed with its function declarations (prototypes)

- Let's fix this. We can separate the class declaration from its definition, just like a function prototype.

Triangle ADT

Triangle.h

```
class Triangle {
  //OVERVIEW: a geometric representation of a
  //          triangle

  //...
};
```

- Put only the class declaration (no implementations) in the file `Triangle.h`
- This file contains only the abstraction
- A single OVERVIEW comment describes the class as a whole

Triangle ADT

Triangle.h

```
class Triangle {
  //OVERVIEW: a geometric representation of a
  //          triangle

public:
  //...
};
```

- We'll put the `public` parts first
- The order of `public` and `private` doesn't matter

Triangle ADT

Triangle.h

```
class Triangle {
  //...
 public:
  //EFFECTS: creates a zero size Triangle
  Triangle();

  //REQUIRES: a,b,c are non-negative and form a
  //          triangle
  //EFFECTS: creates a triangle from edge lengths
  Triangle(double a_in, double b_in,double c_in);
};
```

- Add constructors
- Each function must have a specification comment

Triangle ADT

Triangle.h

```
class Triangle {
  //...
 public:
  Triangle();
  Triangle(double a_in, double b_in,double c_in);

   //EFFECTS: returns the area of this Triangle
  double area() const;
  //EFFECTS: prints edge lengths
  void print() const;
};
```

- Add member functions

const member functions

```
class Triangle {
  //...
  double area() const;
  void print() const;
};
```

- This is a new use of `const`, and it means "this member function promises not to modify any member variable"
- We have now seen three uses of `const`:
  1. `const int* p;` // the pointed-to object cannot change
  2. `int *const p;` // the pointer cannot change
  3. `void foo() const;` // member function cannot change member variable

Triangle ADT

Triangle.h

```
class Triangle {
  //...
 public:
  Triangle();
  Triangle(double a_in, double b_in,double c_in);
  double area() const;
  void print() const;
 private:
   //edges are non-negative and form a triangle
   double a,b,c;
};
```

- Add member variables

Representation invariant

Triangle.h

```
class Triangle {
  //...
  //edges are non-negative and form a triangle
  double a,b,c;
};
```

- Member variables are a class's representation
- The description of how member variables should behave are *representation invariants*
- Representation invariants are rules that the representation must obey immediately before and immediately after any member function execution

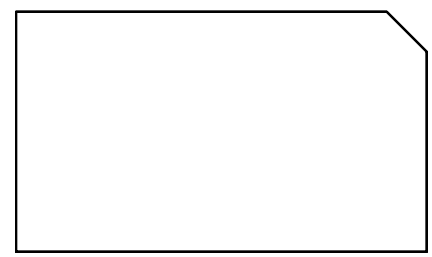
What vs. How

- We now have an **abstract** description of values and operations.
  - *What* the data type does, but not *how*

`Triangle.h`

- Now, we need to implement this ADT
  - *How* the data type works

`Triangle.cpp`



Triangle ADT

Triangle.cpp

```
#include "Triangle.h"
#include <cmath>
#include <iostream>
using namespace std;
```

- Implementations go in `Triangle.cpp`
- `#include "Triangle.h"` tells the compiler to “copy-paste” `Triangle.h` at the top of this file

Triangle ADT

Triangle.cpp

```
//...
Triangle::Triangle()
  : a(0), b(0), c(0) {}
```

- Implement default constructor
- `::` is the scope resolution operator, which tells the compiler that this function is inside the scope of the `Triangle` class
- Needed so that the compiler knows that this is a *member* function inside `Triangle`

Triangle ADT

Triangle.cpp

```
//...
Triangle::Triangle()
   : a(0), b(0), c(0) {}
```

- This syntax is called an *initializer list*
- This code work the same way as this:
  `Triangle::Triangle() { a=b=c=0; }`
- But it is more efficient

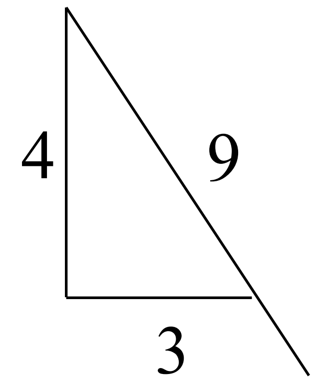
Triangle ADT

Triangle.cpp

```
Triangle::Triangle(double a_in, double b_in, double c_in)
 : a(a_in), b(b_in), c(c_in) {}
```

- The second constructor, also uses an initializer list
- Pitfall: The order in which elements are initialized is the order they appear in the object, NOT the order in the initialization list
- It is customary to keep them in the same order to avoid confusion

Recall assert()

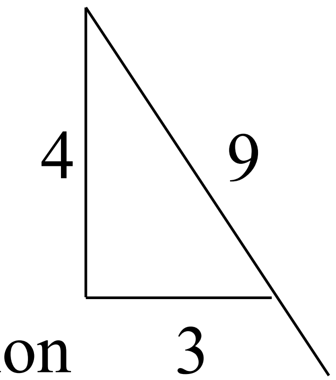


- `assert()` is a programmer's friend for debugging
- Does nothing if statement `STATEMENT` is true
- Exits and prints an error message if `STATEMENT` is false
- We can *assert* that the representation invariant is true

Triangle.cpp

```
Triangle::Triangle(double a_in, double b_in, double c_in)
 : a(a_in), b(b_in), c(c_in) {
  assert( /*STATEMENT*/ );
}
```

Exercise

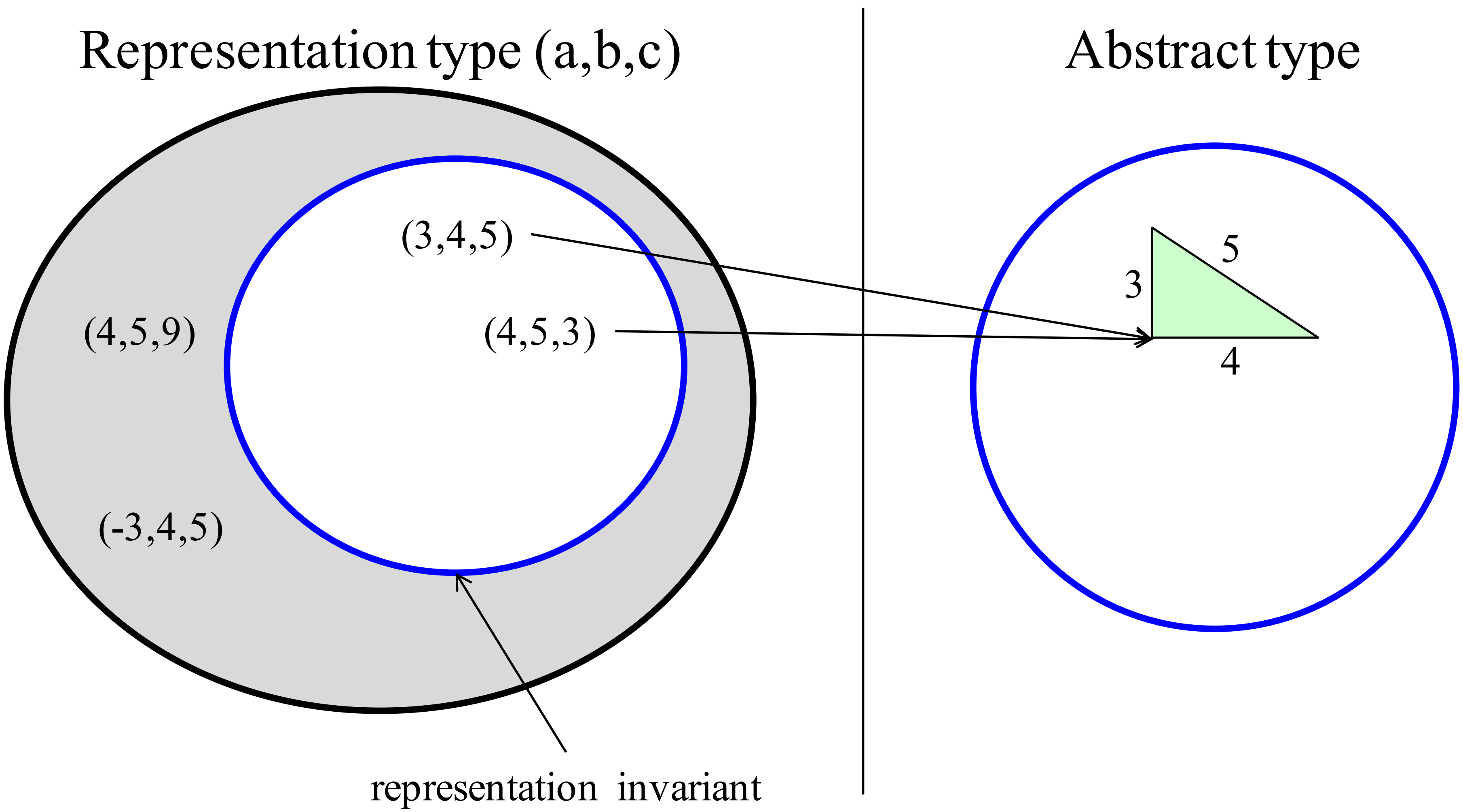


- Write an assert statement that checks the representation invariant
  - Edges are non-negative and form a triangle
  - The sum of the lengths of any two sides of a triangle always exceeds the length of the third side

Triangle.cpp

```
Triangle::Triangle(double a_in, double b_in, double c_in)
 : a(a_in), b(b_in), c(c_in) {
  assert( /*STATEMENT*/ );
}
```

Representation invariant



Triangle ADT

Triangle.cpp

```
//...
double Triangle::area() const {
  double s = (a + b + c) / 2;
  return sqrt(s*(s-a)*(s-b)*(s-c));
}

void Triangle::print() const {
  cout << "a=" << a << " b=" << b << " c=" << c
       << endl;
}
```

- Implementations for `print()` and `area()`

Using our ADT

- We now have an abstract description of values and operations
  - *What* the data type does, but not *how*

Triangle.h

- We have an implementation of this ADT
  - *How* the data type works

Triangle.cpp

- Now, let's use our new ADT

Graphics.cpp

Cartoon credit: xkcd.com

Graphics.cpp

A use for triangles

- In computer graphics, 3D surfaces can be modeled using connected triangles, called a triangle mesh
- Let’s calculate the area of this surface

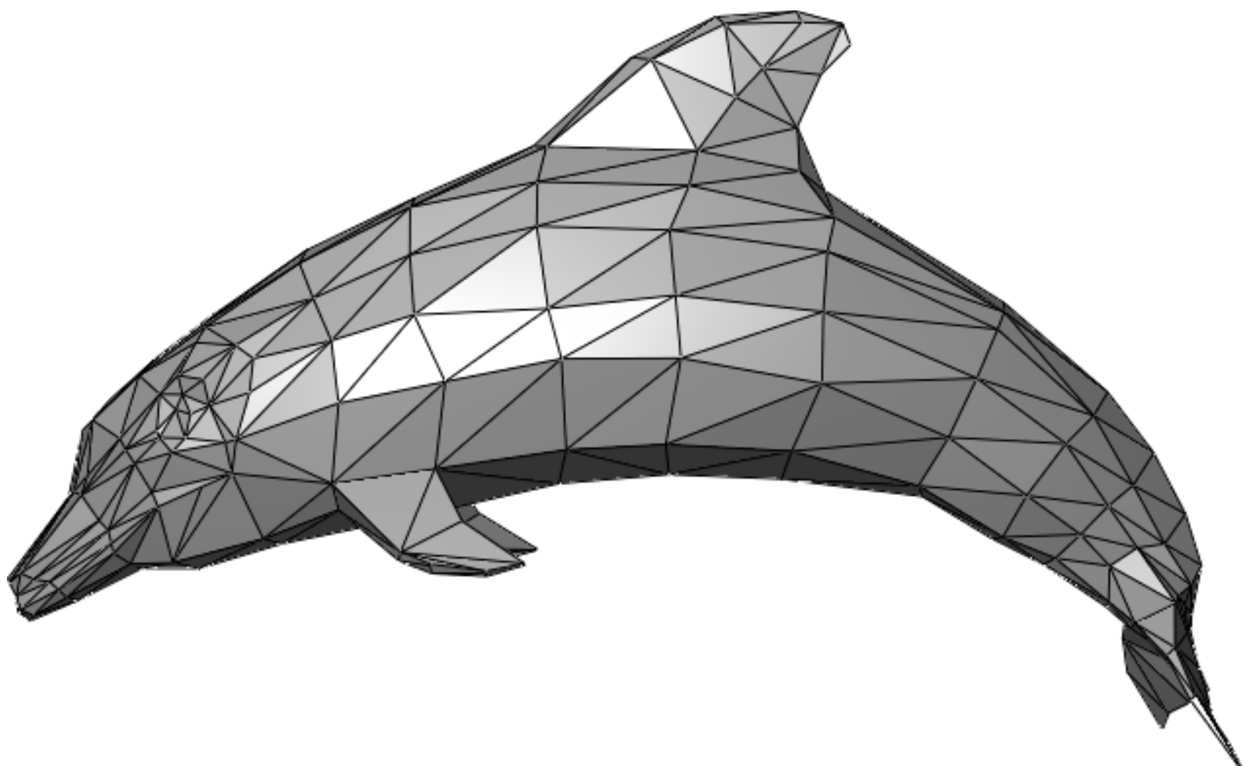


Image: wikipedia.org

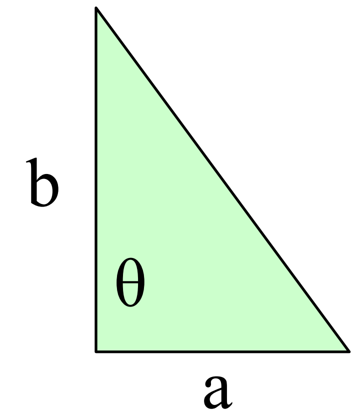
Graphics.cpp

Triangle ADT

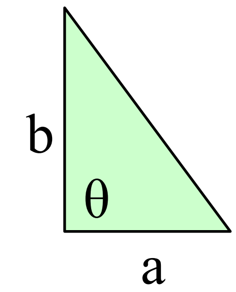
```
#include "Triangle.h"
int main() {
  const int SIZE = 3;
  Triangle mesh[SIZE];
  // fill with triangles ...

  double area = 0;
  for (int i=0; i<SIZE; ++i) {
    area += mesh[i].area();
  }
  cout << "total area = " << area << "\n";
}
```

```
$ g++ Graphics.cpp Triangle.cpp
$ ./a.out
total area = 22.3196
```

Exercise



- There is more than one way to represent a triangle
- Let's change our representation from 3 edges to 2 edges and an angle: `a`, `b`, and `theta`
- Do we need to change *what* our ADT does?
- Do we need to change *how* our ADT does it?
- Do we need to change anything in `Triangle.h`? What?
- Do we need to change anything in `Triangle.cpp`? What?
- Do we need to change anything in `Graphics.cpp`? What?
- Will Alice, Bob or both need to change their code?

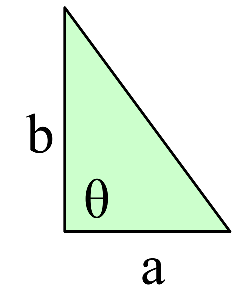


Solution

- Do we need to change *what* our ADT does?
  - No, don't touch `public` function inputs or outputs

- Do we need to change *how* our ADT does it?
  - Yes, because internal representation is different now

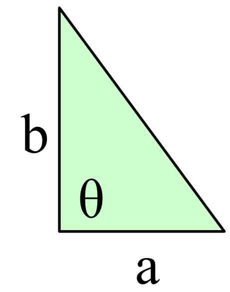
Solution



- Do we need to change anything in `Triangle.h`? What?
- Yes. Only the `private` member variables

Triangle.h

```
class Triangle {
  //...
 private:
  //edges a and b are separated by angle theta
  //and form a triangle
  double a, b;  //edges - note c is no longer here,
                //   but it still needs to be
                //   accounted for (see next slides)
  double theta; //angle
};
```



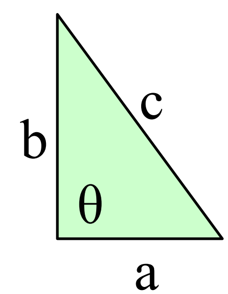
Solution

- Do we need to change anything in `Triangle.cpp`? What?
- Yes. The function implementations change.

```
Triangle::Triangle(double a_in, double b_in, double c_in) {
  a = a_in;
  b = b_in;
  assert(/*...*/);
  theta = acos((a*a + b*b - c_in*c_in) / (2*a*b));
}
```

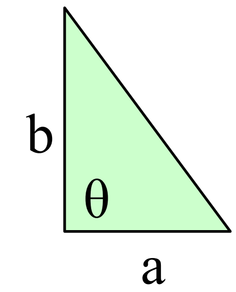
Law of cosigns

$$\Theta = \arccos(\frac{a^2 + b^2 - c^2}{2ab})$$



Note: The default constructor will need to change as well.

Solution



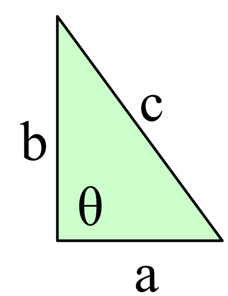
- Do we need to change anything in `Triangle.cpp`? What?
- Yes. The function implementations change.

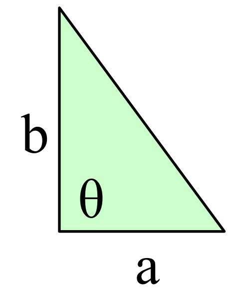
```
Triangle::print() {
  double c = sqrt(a*a + b*b + 2*a*b*cos(theta));
  cout << "a=" << a << " b=" << b << " c=" << c
       << "\n";
}
```

Note: The area() member function will similarly need to change.

<u>Law of cosigns</u>

$$c = \sqrt{a^2 + b^2 - 2ab\cos\Theta}$$



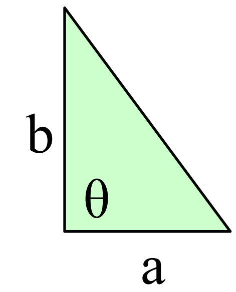


Solution

- Do we need to change anything in `Triangle.cpp`? What?
- Yes. The function implementations change.

```
Triangle::area() {
  return a*b*sin(theta)/2; //simpler!
}
```

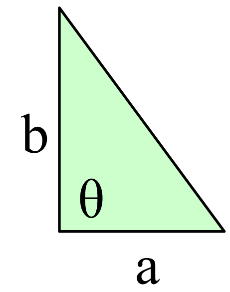
Abstraction exercise



- Do we need to change anything in `Graphics.cpp`? What?
  - No! That's the cool part ☺
- Will Alice, Bob or both need to change their code? Just Alice.

```
int main() {
  //...

  double area = 0;
  for (int i=0; i<SIZE; ++i) {
    area += mesh[i].area();
  }
  cout << "total area = " << area << "\n";
}
```

Graphics.cpp



The power of abstraction

- We changed the implementation, but not the abstraction
  - Modified `private` member variables
  - Modified `public` function implementations
- We changed *how* the abstract data type worked
- We did not change *what* the abstract data type did
- Because the abstraction remained the same, our old code that used the abstract data type still worked
- This is especially important when you have many people working on one project
- This is a big benefit of ADTs!