Chapter Four: Loops

Slides by Evan Gallagher

Chapter Goals

- To implement **`while`, `for` and `do`** loops
- To avoid infinite loops and off-by-one errors
- To understand nested loops
- To implement programs that read and process data sets
- To use a computer for simulations

What Is the Purpose of a Loop?

A loop is a statement that is used to:

execute one or more statements
repeatedly until a goal is reached.

Sometimes these one-or-more statements
will not be executed at all
—if that's the way to reach the goal

The Three Loops in C++

C++ has these three looping statements:

```
while
for
do
```

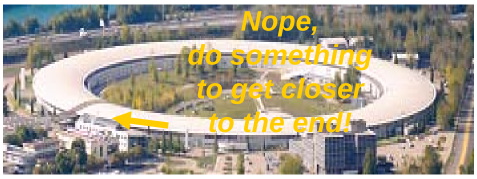
4.1 The `while` Loop

In a particle accelerator, subatomic particles traverse a loop-shaped tunnel multiple times, gaining speed. Similarly, in computer science, statements in a loop are executed *while* a condition is true.

The `while` Loop

The **`while`** statement executes statements
until a condition is true

The `while` Loop



The **`while`** statement executes statements
until a condition is true

The `while` Loop

The **`while`** statement executes statements
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The `while` Loop

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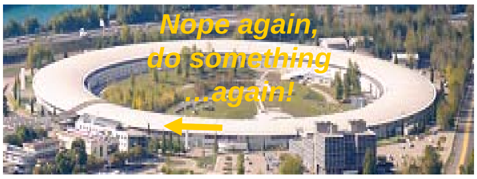
The `while` Loop



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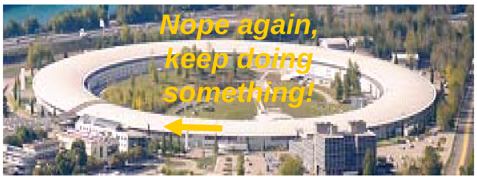
The `while` Loop



The `while` statement executes statements until a condition is true

The `while` Loop

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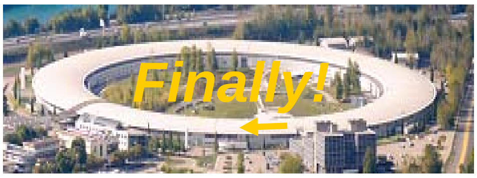
The `while` statement executes statements until a condition is true

The while Loop

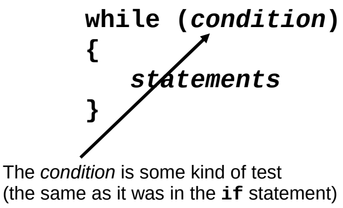


The **while** statement executes statements until a condition is true

The while Loop

The **while** statement executes statements until a condition is true

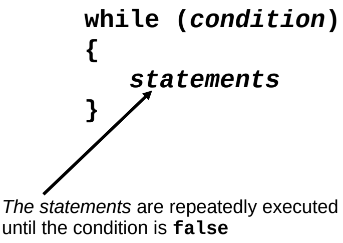
The while Loop



```
while (condition)
{
   statements
}
```

The *condition* is some kind of test
(the same as it was in the **if** statement)

The while Loop



```
while (condition)
{
   statements
}
```

The statements are repeatedly executed
until the condition is **false**

Using a Loop to Solve an Investment Problem.

An investment problem:
Starting with $10,000, how many years until we have at least $20,000?

The algorithm:

1. Start with a year value of 0 and a balance of $10,000.
2. **Repeat** the following steps **while the balance is less than $20,000**:
   - Add 1 to the year value.
   - Compute the interest by multiplying the balance value by 0.05 (5 percent interest) (will be a **const**, of course).
   - Add the interest to the balance.
3. Report the final year value as the answer.

Using a Loop to Solve an Investment Problem.

2. **Repeat** the following steps **while the balance is less than $20,000**:

"Repeat .. while" in the problem indicates a loop is needed.

To reach the goal of being able to report the final year value, adding and multiplying must be repeated some unknown number of times.

Using a Loop to Solve the Investment Problem.

The statements to be controlled are:

- Incrementing the **`year`** variable
- Computing the **`interest`** variable, using a **`const`** for the **`RATE`**
- Updating the **`balance`** variable by adding the **`interest`**

```
year++;
double interest = balance * RATE / 100;
balance = balance + interest;
```

Using a Loop to Solve the Investment Problem.

The condition, which indicates when to ***stop*** executing the statements, is this test:

```
(balance < TARGET)
```

Using a Loop to Solve the Investment Problem.

Here is the complete **`while`** statement:

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

Using a Loop to Solve the Investment Problem.

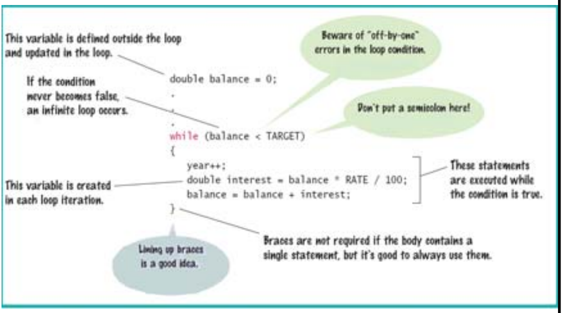
Notice that **`interest`** is defined *inside* the loop and that **`year`** and **`balance`** had to have been defined *outside* the loop.

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

A new **`interest`** variable to be created in *each* iteration.

`year` and **`balance`** are used for *all* iterations.

The `while` Statement



```
double balance = 0;
.
.
.
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

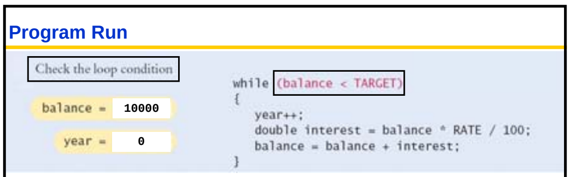
This variable is defined outside the loop and updated in the loop.
If the condition never becomes false, an infinite loop occurs.
Beware of "off-by-one" errors in the loop condition.
Don't put a semicolon here!
These statements are executed while the condition is true.
This variable is created in each loop iteration.
Lining up braces is a good idea.
Braces are not required if the body contains a single statement, but it's good to always use them.

The Complete Investment Program

ch04/doublinv.cpp

```
#include <iostream>
using namespace std;

int main()
{
   const double RATE = 5;
   const double INITIAL_BALANCE = 10000;
   const double TARGET = 2 * INITIAL_BALANCE;

   double balance = INITIAL_BALANCE;
   int year = 0;

   while (balance < TARGET)
   {
      year++;
      double interest = balance * RATE / 100;
      balance = balance + interest;
   }

   cout << "The investment doubled after "
        << year << " years." << endl;

   return 0;
}
```

Program Run



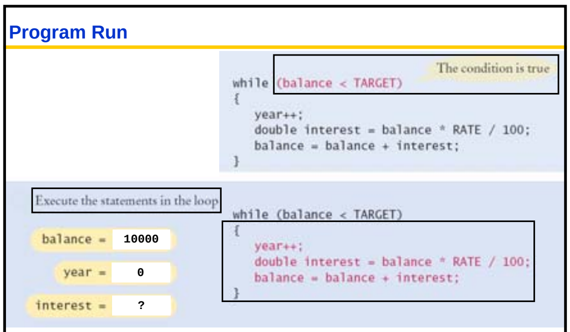
Check the loop condition

balance = 10000

year = 0

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

Program Run



The condition is true

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

Execute the statements in the loop

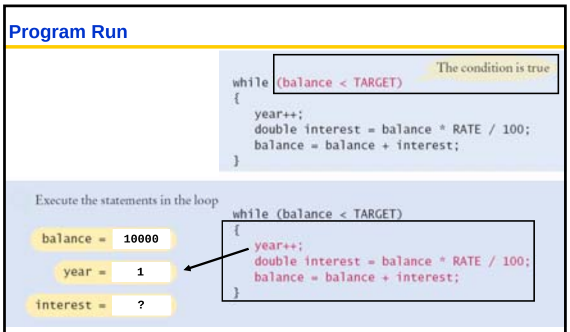
balance = 10000

year = 0

interest = ?

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

Program Run



The condition is true

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

Execute the statements in the loop

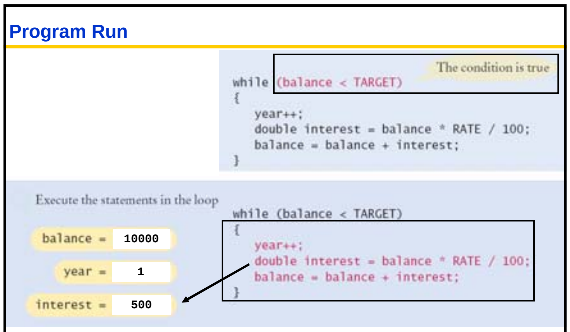
balance = 10000

year = 1

interest = ?

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

Program Run



The condition is true

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

Execute the statements in the loop

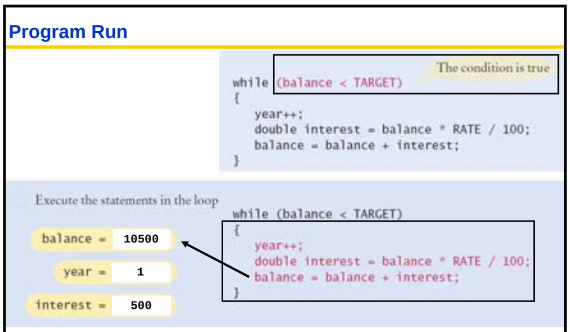
balance = 10000

year = 1

interest = 500

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

Program Run



The condition is true

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

Execute the statements in the loop

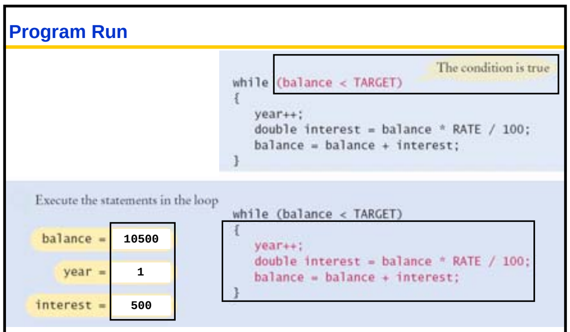
balance = 10500

year = 1

interest = 500

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

Program Run



The condition is true

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

Execute the statements in the loop

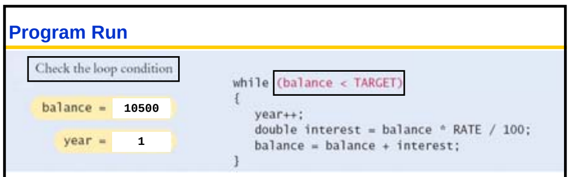
balance = 10500

year = 1

interest = 500

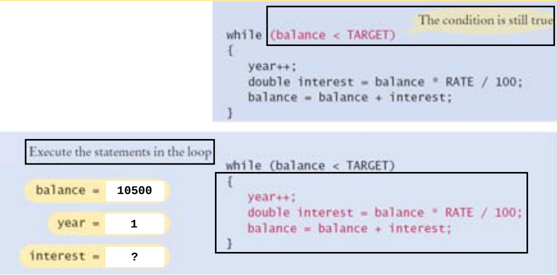
```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

Program Run



```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

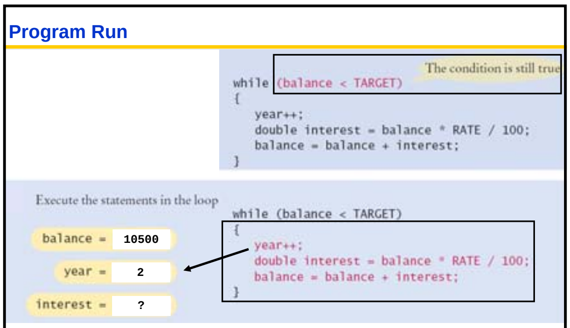
Program Run


The condition is still true
Execute the statements in the loop
balance = 10500
year = 1
interest = ?

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

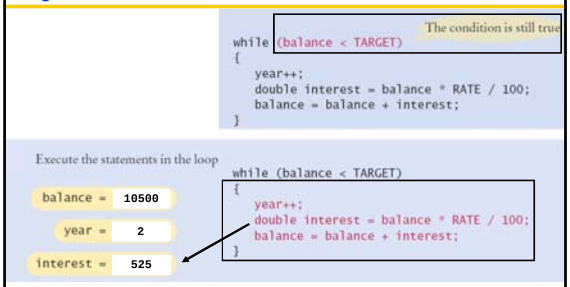
Program Run


The condition is still true
Execute the statements in the loop
balance = 10500
year = 2
interest = ?

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

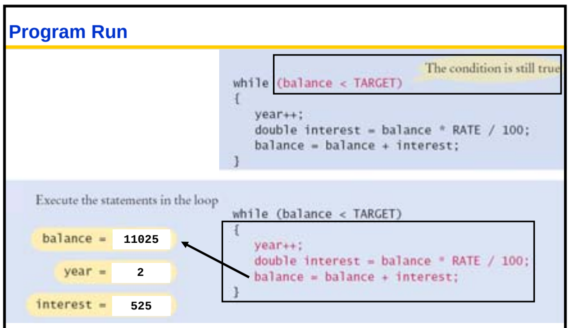
Program Run


The condition is still true
Execute the statements in the loop
balance = 10500
year = 2
interest = 525

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

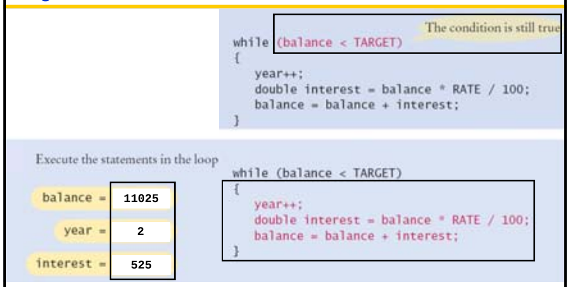
Program Run


The condition is still true
Execute the statements in the loop
balance = 11025
year = 2
interest = 525

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

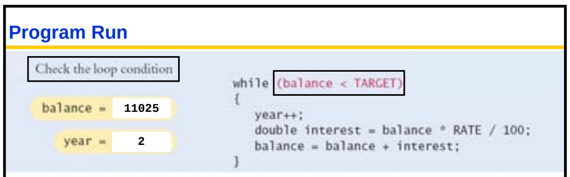
Program Run


The condition is still true
Execute the statements in the loop
balance = 11025
year = 2
interest = 525

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

Program Run



```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

Program Run

before entering while's body		at the end of while's body		
balance	year	interest	balance	year
10000.00	0	500.00	10500.00	1
10500.00	1	525.00	11025.00	2

…this process goes on for 15 iterations…

Program Run

before entering while's body		at the end of while's body		
balance	year	interest	balance	year
10000.00	0	500.00	10500.00	1
10500.00	1	525.00	11025.00	2
11025.00	2	551.25	11576.25	3

…this process goes on for 15 iterations…

Program Run

before entering while's body		at the end of while's body		
balance	year	interest	balance	year
10000.00	0	500.00	10500.00	1
10500.00	1	525.00	11025.00	2
11025.00	2	551.25	11576.25	3
11576.25	3	578.81	12155.06	4
12155.06	4	607.75	12762.82	5

…this process goes on for 15 iterations…

Program Run

before entering while's body		at the end of while's body		
balance	year	interest	balance	year
10000.00	0	500.00	10500.00	1
10500.00	1	525.00	11025.00	2
11025.00	2	551.25	11576.25	3
11576.25	3	578.81	12155.06	4
12155.06	4	607.75	12762.82	5
12762.82	5	638.14	13400.96	6
13400.96	6	670.05	14071.00	7
14071.00	7	703.55	14774.55	8
14774.55	8	738.73	15513.28	9

…this process goes on for 15 iterations…

Program Run

before entering while's body		at the end of while's body		
balance	year	interest	balance	year
10000.00	0	500.00	10500.00	1
10500.00	1	525.00	11025.00	2
11025.00	2	551.25	11576.25	3
11576.25	3	578.81	12155.06	4
12155.06	4	607.75	12762.82	5
12762.82	5	638.14	13400.96	6
13400.96	6	670.05	14071.00	7
14071.00	7	703.55	14774.55	8
14774.55	8	738.73	15513.28	9
15513.28	9	775.66	16288.95	10
16288.95	10	814.45	17103.39	11
17103.39	11	855.17	17958.56	12
17958.56	12	897.93	18856.49	13
18856.49	13	942.82	19799.32	14

…this process goes on for 15 iterations…

Program Run

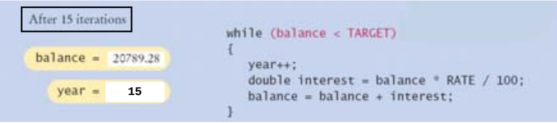
…this process goes on for 15 iterations…

…until the **`balance`** is finally(!) over $20,000 and the test becomes **`false`**.

before entering while's body		at the end of while's body		
balance	year	interest	balance	year
10000.00	0	500.00	10500.00	1
10500.00	1	525.00	11025.00	2
11025.00	2	551.25	11576.25	3
11576.25	3	578.81	12155.06	4
12155.06	4	607.75	12762.82	5
12762.82	5	638.14	13400.96	6
13400.96	6	670.05	14071.00	7
14071.00	7	703.55	14774.55	8
14774.55	8	738.73	15513.28	9
15513.28	9	775.66	16288.95	10
16288.95	10	814.45	17103.39	11
17103.39	11	855.17	17958.56	12
17958.56	12	897.93	18856.49	13
18856.49	13	942.83	19799.32	14
19799.32	14	989.97	20789.28	15

while statement is over

Program Run



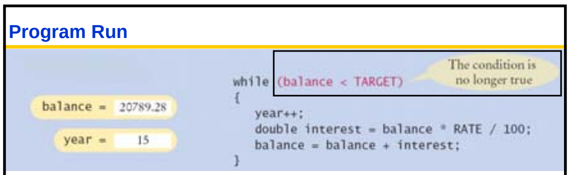
After 15 iterations

balance = 20789.28

year = 15

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

Program Run



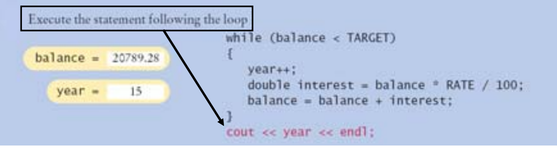
balance = 20789.28

year = 15

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
```

The condition is no longer true

Program Run



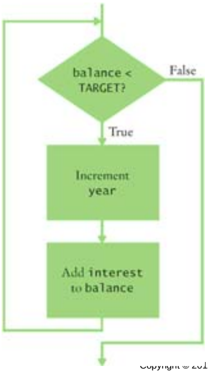
Execute the statement following the loop

balance = 20789.28

year = 15

```
while (balance < TARGET)
{
   year++;
   double interest = balance * RATE / 100;
   balance = balance + interest;
}
cout << year << endl;
```

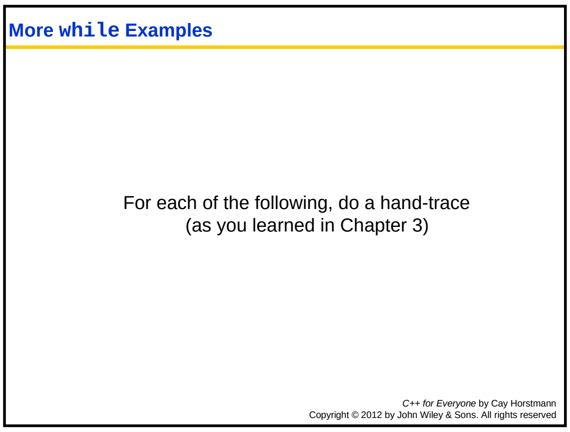
Flowchart of the Investment Calculation's `while` Loop



More `while` Examples

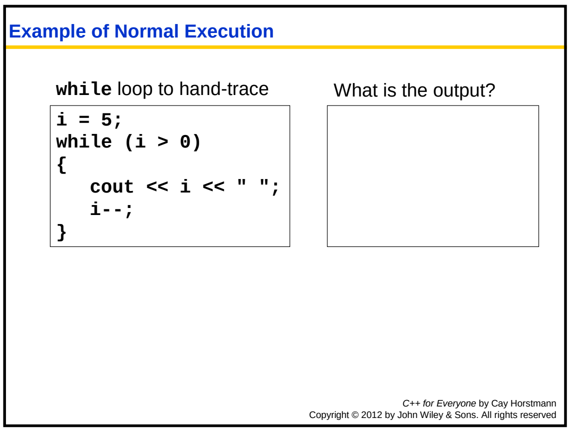
Skip the examples?

NO   YES



More while Examples

For each of the following, do a hand-trace
(as you learned in Chapter 3)

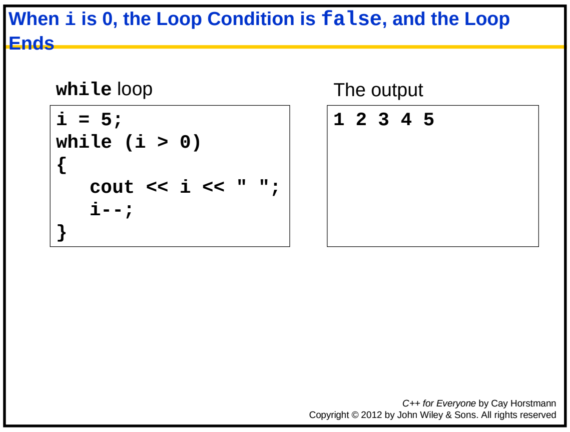


Example of Normal Execution

while loop to hand-trace

```
i = 5;
while (i > 0)
{
   cout << i << " ";
   i--;
}
```

What is the output?



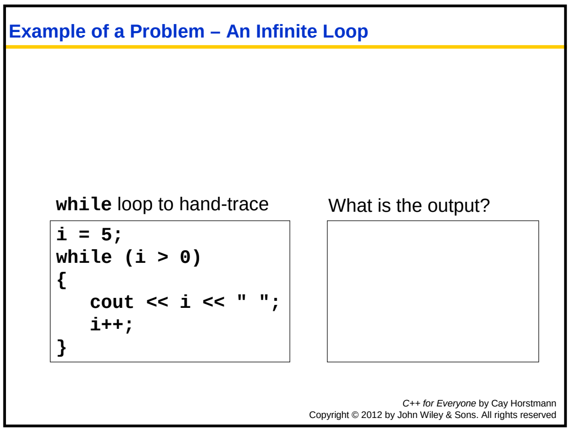
When i is 0, the Loop Condition is false, and the Loop Ends

while loop

```
i = 5;
while (i > 0)
{
   cout << i << " ";
   i--;
}
```

The output

```
1 2 3 4 5
```

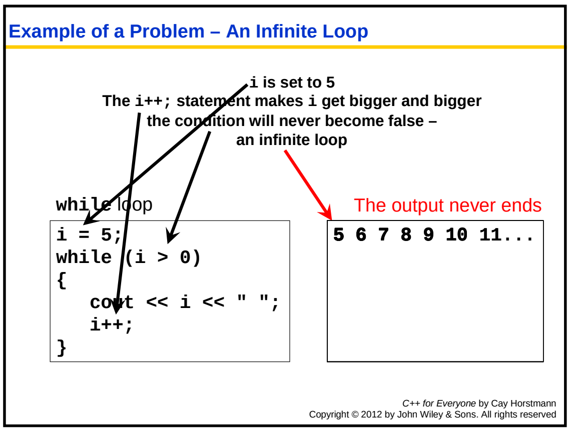


Example of a Problem – An Infinite Loop

while loop to hand-trace

```
i = 5;
while (i > 0)
{
   cout << i << " ";
   i++;
}
```

What is the output?



Example of a Problem – An Infinite Loop

i is set to 5

The i++; statement makes i get bigger and bigger

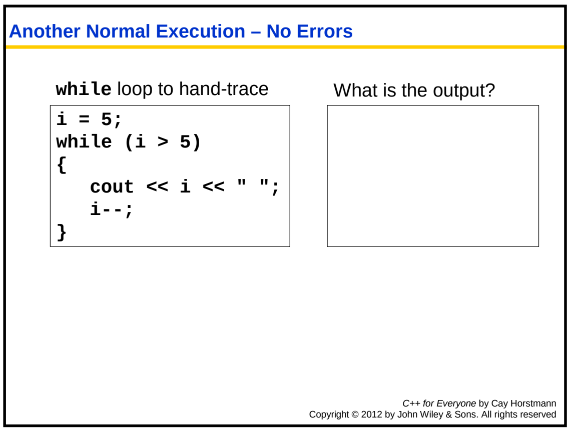
the condition will never become false –
an infinite loop

while loop

```
i = 5;
while (i > 0)
{
   cout << i << " ";
   i++;
}
```

The output never ends

```
5 6 7 8 9 10 11...
```



Another Normal Execution – No Errors

while loop to hand-trace

```
i = 5;
while (i > 5)
{
   cout << i << " ";
   i--;
}
```

What is the output?

Another Normal Execution – No Errors

while loop

```
i = 5;
while (i > 5)
{
   cout << i << " ";
   i--;
}
```

There is (correctly) no output

The expression **i > 5** is initially false, so the statements are never executed.

Another Normal Execution – No Errors

while loop

```
i = 5;
while (i > 5)
{
   cout << i << " ";
   i--;
}
```

There is (correctly) no output

This is not a error.

Sometimes we *do not* want to execute the statements *unless* the test is true.

Normal Execution with Another “Programmer’s Error”

while loop to hand-trace

```
i = 5;
while (i < 0)
{
   cout << i << " ";
   i--;
}
```

What is the output?

Normal Execution with Another “Programmer’s Error”

The programmer probably thought:
“Stop when **i** is less than 0”.

However, the loop condition controls when the loop is *executed* - not when it *ends*.

while loop

```
i = 5;
while (i < 0)
{
   cout << i << " ";
   i--;
}
```

Again, there is no output

A Very Difficult Error to Find (especially after looking for it for hours and hours!)

while loop to hand-trace

```
i = 5;
while (i > 0);
{
   cout << i << " ";
   i--;
}
```

What is the output?

A Very Difficult Error to Find (especially after looking for it for hours and hours!)

Another infinite loop – caused by a single character: **;**

That semicolon causes the **while** loop to have an “empty body” which is executed forever.

The **i** in **(i > 0)** is never changed.

while loop

```
i = 5;
while (i > 0);
{
   cout << i << " ";
   i--;
}
```

There is no output!

Common Error – Infinite Loops

C++ for Everyone by Cay Horstmann

Common Error – Infinite Loops

C++ for Everyone by Cay Horstmann

Common Error – Infinite Loops

C++ for Everyone by Cay Horstmann

Common Error – Infinite Loops

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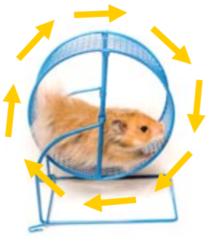
Common Error – Infinite Loops

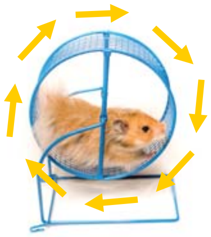


C++ for Everyone by Cay Horstmann

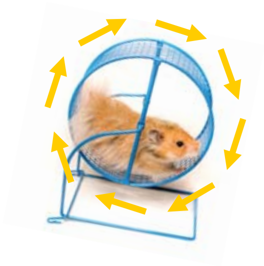
Common Error – Infinite Loops

Common Error – Infinite Loops

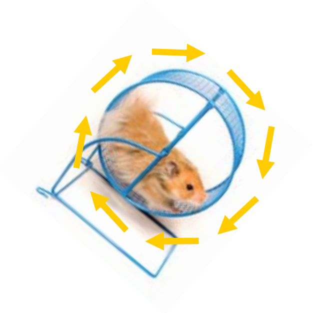
Common Error – Infinite Loops



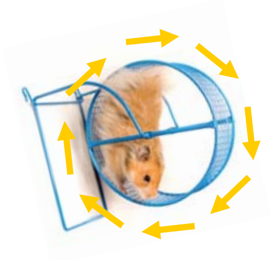
Common Error – Infinite Loops

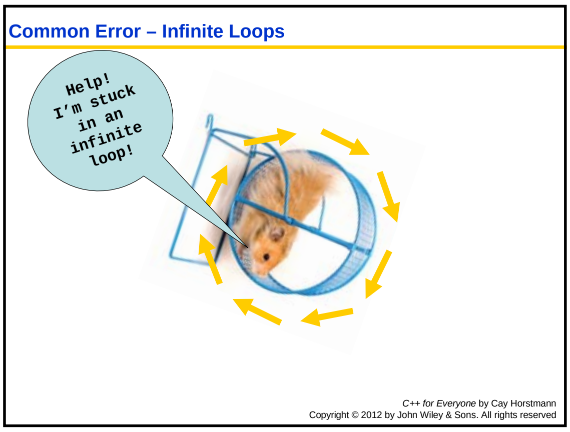


Common Error – Infinite Loops

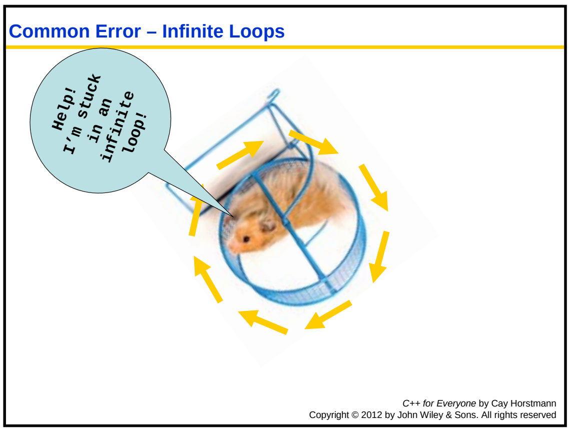


Common Error – Infinite Loops

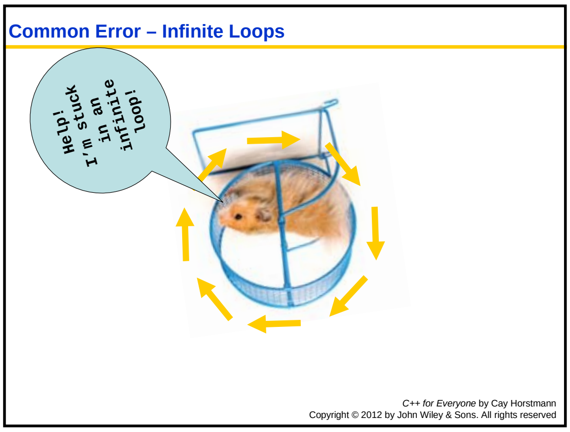




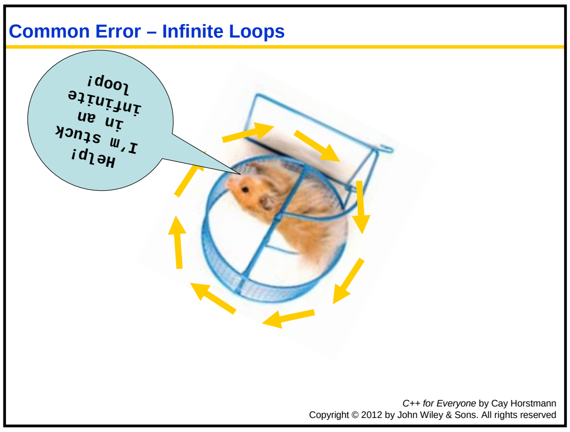
Common Error – Infinite Loops



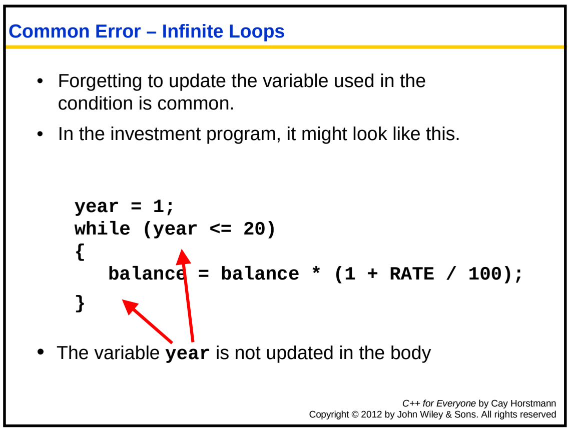
Common Error – Infinite Loops



Common Error – Infinite Loops



Common Error – Infinite Loops

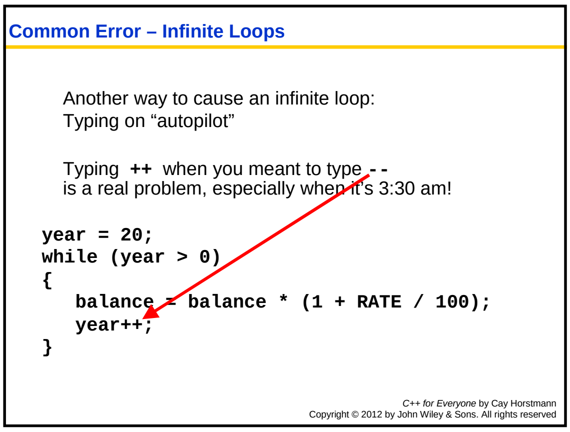


Common Error – Infinite Loops

- Forgetting to update the variable used in the condition is common.
- In the investment program, it might look like this.

```
year = 1;
while (year <= 20)
{
   balance = balance * (1 + RATE / 100);
}
```

- The variable **`year`** is not updated in the body



Common Error – Infinite Loops

Another way to cause an infinite loop:
Typing on "autopilot"

Typing **`++`** when you meant to type **`--`**
is a real problem, especially when it's 3:30 am!

```
year = 20;
while (year > 0)
{
   balance = balance * (1 + RATE / 100);
   year++;
}
```

A Not Really Infinite Infinite Loop

- Due to what is called “wrap around”, the previous loop ***will*** end.
- At some point the value stored in the **`int`** variable gets to the largest representable positive integer. When it is incremented, the value stored “wraps around” to be a negative number.

That definitely stops the loop!

Common Error – Are We There Yet?

Well, are we?

Common Error – Are We There Yet?

When doing something repetitive,
most of us want to know when we are done.

For example, you may think,
“I want to get at least $20,000,”
and set the loop condition to

```
while (balance >= TARGET)
```

wrong test

Common Error – Are We There Yet?

But the **`while`** loop thinks the opposite:
How long am I allowed to keep going?

What is the correct loop condition?

```
while (                    )
```

Common Error – Are We There Yet?

But the **`while`** loop thinks the opposite:
How long am I allowed to keep going?

What is the correct loop condition?

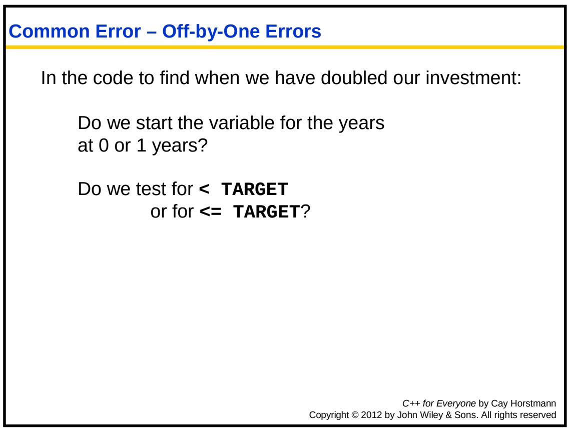
```
while (balance < TARGET)
```

In other words:
“Keep at it while the balance
is less than the target”.

Common Error – Are We There Yet?

When writing a loop condition, don’t ask, “Are we there yet?”

The *condition* determines how long the loop will keep going.

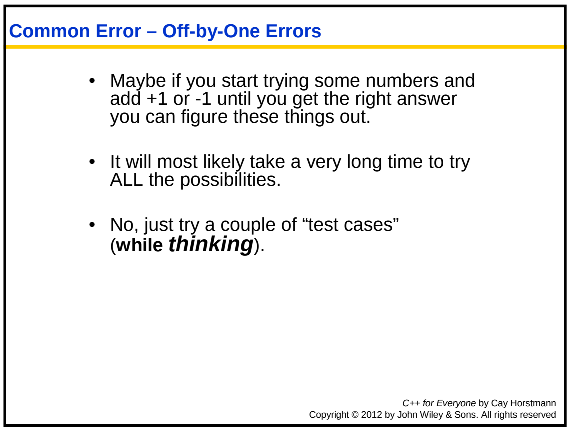


Common Error – Off-by-One Errors

In the code to find when we have doubled our investment:

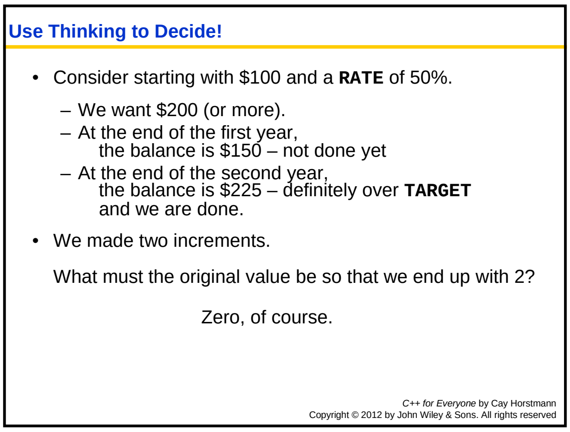
Do we start the variable for the years
at 0 or 1 years?

Do we test for `< TARGET`
or for `<= TARGET`?



Common Error – Off-by-One Errors

- Maybe if you start trying some numbers and add +1 or -1 until you get the right answer you can figure these things out.
- It will most likely take a very long time to try ALL the possibilities.
- No, just try a couple of “test cases” (**while *thinking***).

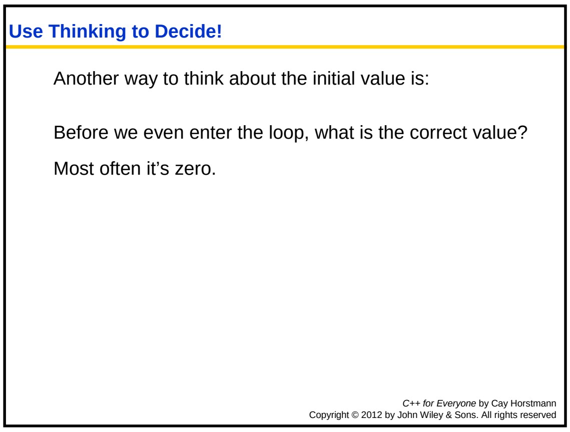


Use Thinking to Decide!

- Consider starting with $100 and a `RATE` of 50%.
  - We want $200 (or more).
  - At the end of the first year,
    the balance is $150 – not done yet
  - At the end of the second year,
    the balance is $225 – definitely over `TARGET`
    and we are done.
- We made two increments.

  What must the original value be so that we end up with 2?

  Zero, of course.

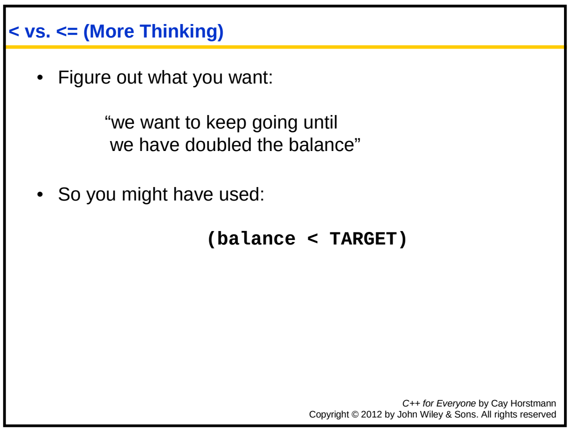


Use Thinking to Decide!

Another way to think about the initial value is:

Before we even enter the loop, what is the correct value?

Most often it’s zero.



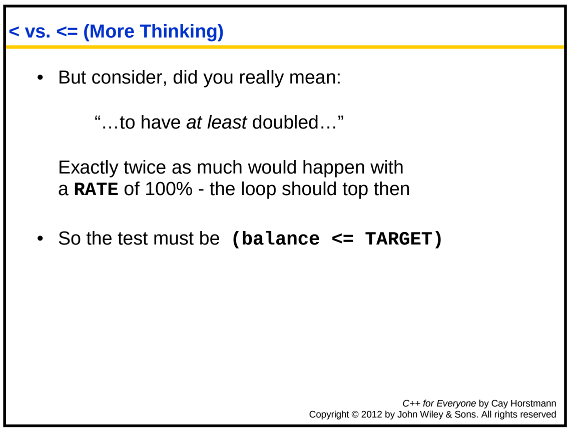
< vs. <= (More Thinking)

- Figure out what you want:

  “we want to keep going until
  we have doubled the balance”

- So you might have used:

  `(balance < TARGET)`



< vs. <= (More Thinking)

- But consider, did you really mean:

  “…to have *at least* doubled…”

  Exactly twice as much would happen with
  a `RATE` of 100% - the loop should top then

- So the test must be `(balance <= TARGET)`

4.2 Problem Solving: Hand-Tracing

Hand-tracing is a method of checking your work.

To do a hand-trace, write your variables on a sheet of paper and mentally execute each step of your code…

> writing down the values of the variables
> as they are changed in the code.

Cross out the old value and write down the new value as they are changed – that way you can also see the history of the values.

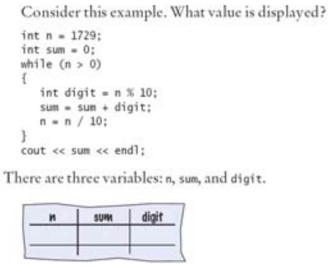
Problem Solving: Hand-Tracing

To keep up with which statement is about to be executed you should use a marker.
Preferably something that doesn't obliterate the code:

Like a paper clip.

(No, not that infamous one!)

Problem Solving: Hand-Tracing



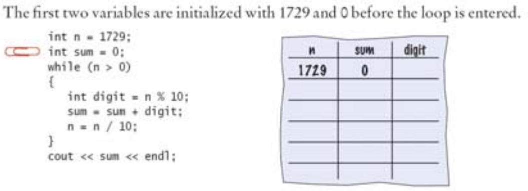
Consider this example. What value is displayed?

```
int n = 1729;
int sum = 0;
while (n > 0)
{
   int digit = n % 10;
   sum = sum + digit;
   n = n / 10;
}
cout << sum << endl;
```

There are three variables: n, sum, and digit.

n	sum	digit

Problem Solving: Hand-Tracing

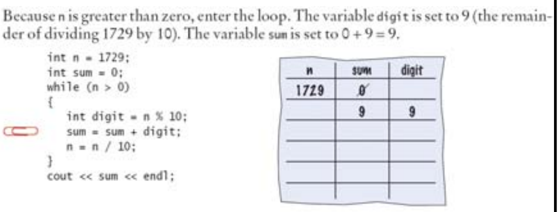


The first two variables are initialized with 1729 and 0 before the loop is entered.

```
int n = 1729;
int sum = 0;
while (n > 0)
{
   int digit = n % 10;
   sum = sum + digit;
   n = n / 10;
}
cout << sum << endl;
```

n	sum	digit
1729	0	

Problem Solving: Hand-Tracing

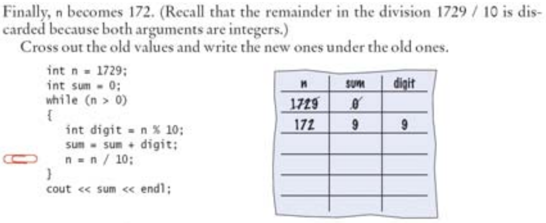


Because n is greater than zero, enter the loop. The variable digit is set to 9 (the remainder of dividing 1729 by 10). The variable sum is set to 0 + 9 = 9.

```
int n = 1729;
int sum = 0;
while (n > 0)
{
   int digit = n % 10;
   sum = sum + digit;
   n = n / 10;
}
cout << sum << endl;
```

n	sum	digit
1729	~~0~~	
	9	9

Problem Solving: Hand-Tracing



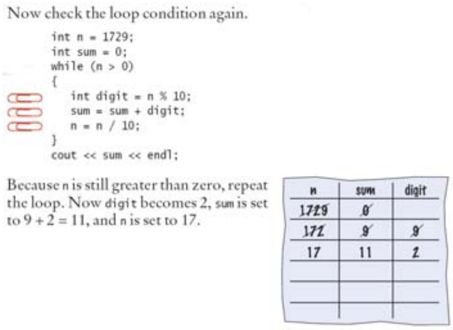
Finally, n becomes 172. (Recall that the remainder in the division 1729 / 10 is discarded because both arguments are integers.)

Cross out the old values and write the new ones under the old ones.

```
int n = 1729;
int sum = 0;
while (n > 0)
{
   int digit = n % 10;
   sum = sum + digit;
   n = n / 10;
}
cout << sum << endl;
```

n	sum	digit
~~1729~~	~~0~~	
172	9	9

Problem Solving: Hand-Tracing



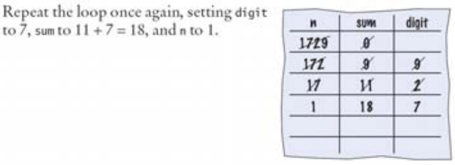
Now check the loop condition again.

```
int n = 1729;
int sum = 0;
while (n > 0)
{
   int digit = n % 10;
   sum = sum + digit;
   n = n / 10;
}
cout << sum << endl;
```

Because n is still greater than zero, repeat the loop. Now digit becomes 2, sum is set to 9 + 2 = 11, and n is set to 17.

n	sum	digit
~~1729~~	~~0~~	
~~172~~	~~9~~	~~9~~
17	11	2

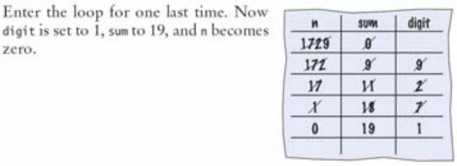
Problem Solving: Hand-Tracing



Repeat the loop once again, setting digit to 7, sum to 11 + 7 = 18, and n to 1.

n	sum	digit
~~1729~~	~~0~~	
~~172~~	~~9~~	~~9~~
~~17~~	~~11~~	~~2~~
1	18	7

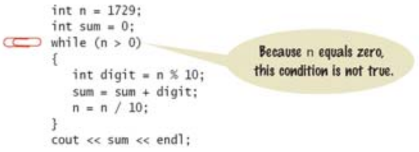
Problem Solving: Hand-Tracing



Enter the loop for one last time. Now digit is set to 1, sum to 19, and n becomes zero.

n	sum	digit
~~1729~~	~~0~~	
~~172~~	~~9~~	~~9~~
~~17~~	~~11~~	~~2~~
~~1~~	~~18~~	~~7~~
0	19	1

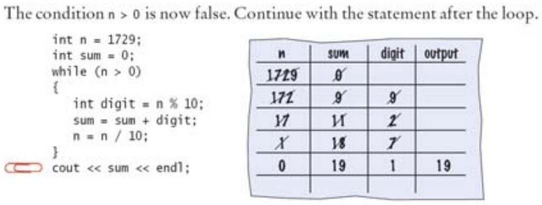
Problem Solving: Hand-Tracing



```
int n = 1729;
int sum = 0;
while (n > 0)
{
   int digit = n % 10;
   sum = sum + digit;
   n = n / 10;
}
cout << sum << endl;
```

Because n equals zero, this condition is not true.

Problem Solving: Hand-Tracing

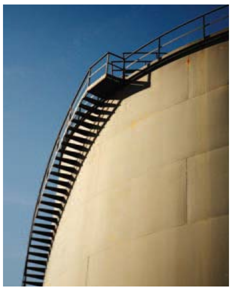


The condition n > 0 is now false. Continue with the statement after the loop.

```
int n = 1729;
int sum = 0;
while (n > 0)
{
   int digit = n % 10;
   sum = sum + digit;
   n = n / 10;
}
cout << sum << endl;
```

n	sum	digit	output
~~1729~~	~~0~~		
~~172~~	~~9~~	~~9~~	
~~17~~	~~11~~	~~2~~	
~~1~~	~~18~~	~~7~~	
0	19	1	19

4.3 The `for` Loop



"You ***"simply"*** take 4,522 steps!!!

To execute statements a certain number of times

The for Loop

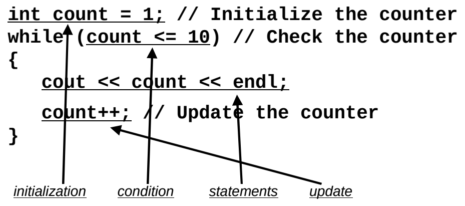
Often you will need to execute a sequence of statements a given number of times.

You could use a **while** loop for this.

```
counter = 1; // Initialize the counter
while (counter <= 10) // Check the counter
{
   cout << counter << endl;
   counter++; // Update the counter
}
```

The for Loop Is Better than while for Doing Certain Things

Consider this code which writes the values 1 through 10 on the screen:



```
int count = 1; // Initialize the counter
while (count <= 10) // Check the counter
{
   cout << count << endl;
   count++; // Update the counter
}
```

The for Loop

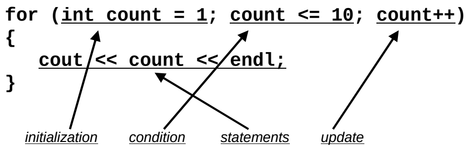
C++ has a statement custom made ***for*** this sort of processing:

the **for** loop.

```
for (counter = 1; counter <= 10; counter++)
{
   cout << counter << endl;
}
```

The for Loop Is Better than while for Doing Certain Things

Doing something a certain number of times or causing a variable to take on a sequence of values is so common, C++ has a statement just for that:



```
for (int count = 1; count <= 10; count++)
{
   cout << count << endl;
}
```

The for Loop

```
for (initialization; condition; update)
{
   statements
}
```

The *initialization* is code that happens once, before the check is made, in order to set up for counting how many times the *statements* will happen. The loop variable is created here.

The for Loop

```
for (initialization; condition; update)
{
   statements
}
```

The *condition* is code that tests to see if the loop is done. When this test is false, the **for** statement is over and we go on to the next statement.

The `for` Loop

```
for (initialization; condition; update)
{
   statements
}
```

The *statements* are repeatedly executed
 - until the condition is false.

The `for` Loop

```
for (initialization; condition; update)
{
   statements
}
```

The *update* is code that causes the condition to eventually become false.

Usually it's incrementing or decrementing the loop variable.

The `for` Loop

Some people call the **`for`** loop *count-controlled*.

In contrast, the **`while`** can be called an *event-controlled* loop because it executes until an event occurs (for example, when the balance reaches the target).

The `for` Loop

Another commonly-used term for a count-controlled loop is *definite*.

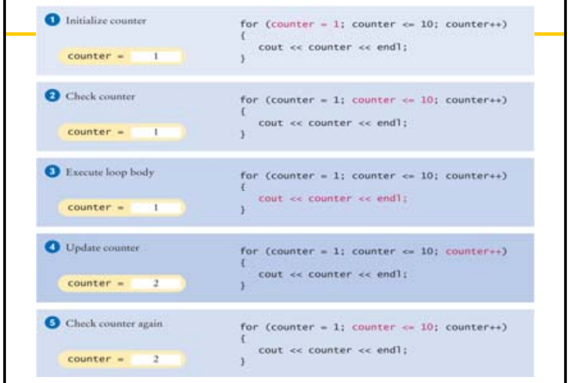
You know from the outset that the loop body will be executed a definite number of times—ten times in our example.

In contrast, you did not know how many iterations it would take to accumulate a target balance in the **`while`** loop code.
Such a loop is called *indefinite*.

Execution of a `for` Statement

Consider this **`for`** statement:

```
int counter;
for (counter = 1; counter <= 10; counter++)
{
   cout << counter << endl;
}
```



1 Initialize counter

counter = 1

```
for (counter = 1; counter <= 10; counter++)
{
   cout << counter << endl;
}
```

2 Check counter

counter = 1

```
for (counter = 1; counter <= 10; counter++)
{
   cout << counter << endl;
}
```

3 Execute loop body

counter = 1

```
for (counter = 1; counter <= 10; counter++)
{
   cout << counter << endl;
}
```

4 Update counter

counter = 2

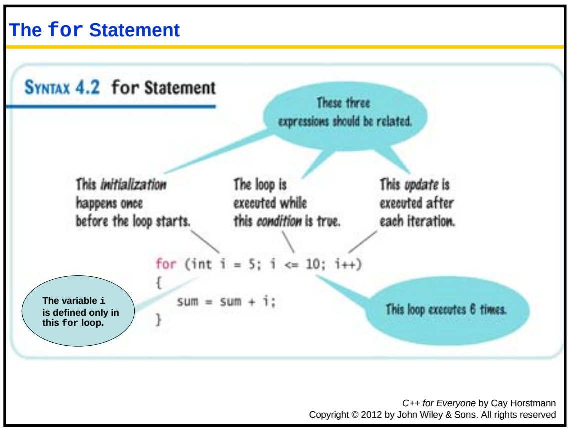
```
for (counter = 1; counter <= 10; counter++)
{
   cout << counter << endl;
}
```

5 Check counter again

counter = 2

```
for (counter = 1; counter <= 10; counter++)
{
   cout << counter << endl;
}
```

The `for` Statement


Syntax 4.2 for Statement
These three expressions should be related.
This initialization happens once before the loop starts.
The loop is executed while this condition is true.
This update is executed after each iteration.
This loop executes 6 times.
The variable i is defined only in this for loop.

```
for (int i = 5; i <= 10; i++)
{
   sum = sum + i;
}
```

Scope of the Loop Variable – Part of the `for` or Not?

- The “loop variable” when defined as part of the **`for`** statement cannot be used before or after the **`for`** statement – it only exists as part of the **`for`** statement and should not need to be used anywhere else in a program.

- A **`for`** statement can use variables that are not part of it, but they should not be used as the loop variable.

(In an earlier example, **`counter`** was defined before the loop – so it does work. Normally **`counter`** would be defined in the *initialization*.)

The `for` Can Count Up or Down

A **`for`** loop can count down instead of up:

```
for (counter = 10; counter >= 0; counter--)…
```

The increment or decrement need not be in steps of 1:

```
for (cntr = 0; cntr <= 10; cntr = + 2)…
```

Notice that in these examples, the loop variable is defined **in** the *initialization* (where it really should be!).

Solving a Problem with a `for` Statement

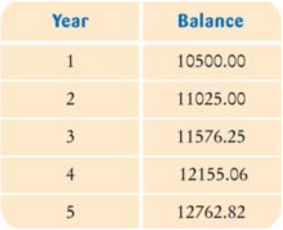
- Earlier we determined the number of years it would take to (at least) double our balance.
- Now let’s see the interest in action:
  - We want to print the balance of our savings account over a five-year period.

  The “…over a five-year period” indicates that a **`for`** loop should be used.

  Because we know how many times the statements must be executed, we choose a **`for`** loop.

Solving a Problem with a `for` Statement

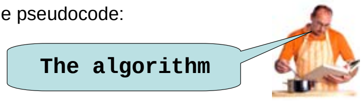
The output should look something like this:



Year	Balance
1	10500.00
2	11025.00
3	11576.25
4	12155.06
5	12762.82

Solving a Problem with a `for` Statement

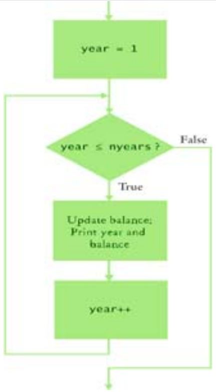
The pseudocode:



```
for (int year = 1; year <= nyears; year++)
{
    Update balance.
    Print year and balance.
}
```

The `for` Loop

Flowchart of
the investment
calculation
using
a **`for`** loop



Solving a Problem with a `for` Statement

Two statements should happen five times.
So use a **`for`** statement.

They are:

update balance
print year and balance

```
for (int year = 1; year <= nyears; year++)
{
   // update balance
   // print year and balance
}
```

The Modified Investment Program Using a `for` Loop

ch04/invtable.cpp

```
#include <iostream>
#include <iomanip>
using namespace std;

int main()
{
   const double RATE = 5;
   const double INITIAL_BALANCE = 10000;
   double balance = INITIAL_BALANCE;
   int nyears;
   cout << "Enter number of years: ";
   cin >> nyears;

   cout << fixed << setprecision(2);
   for (int year = 1; year <= nyears; year++)
   {
      balance = balance * (1 + RATE / 100);
      cout << setw(4) << year << setw(10) << balance << endl;
   }

   return 0;
}
```

The Modified Investment Program Using a `for` Loop

A run of the program:

```
Enter number of years: 10
   1 10500.00
   2 11025.00
   3 11576.25
   4 12155.06
   5 12762.82
   6 13400.96
   7 14071.00
   8 14774.55
   9 15513.28
  10 16288.95
```

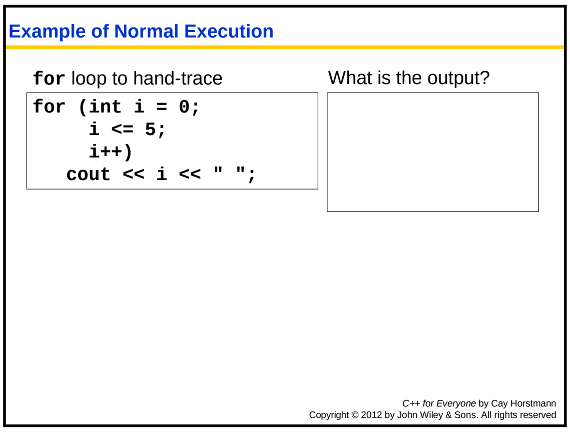
More `for` Examples

Skip the examples?

NO **YES**

More `for` Examples

For each of the following, do a hand-trace.

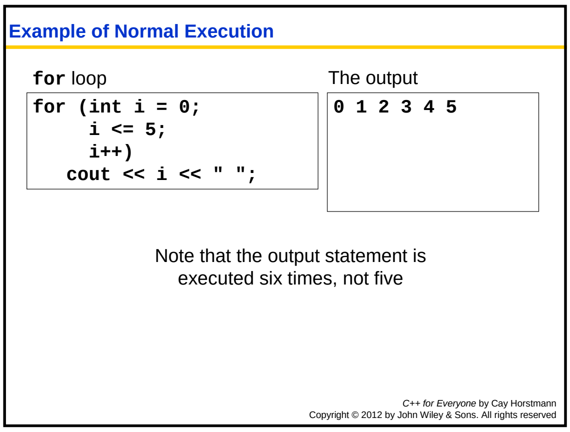


Example of Normal Execution

for loop to hand-trace

```
for (int i = 0;
     i <= 5;
     i++)
   cout << i << " ";
```

What is the output?



Example of Normal Execution

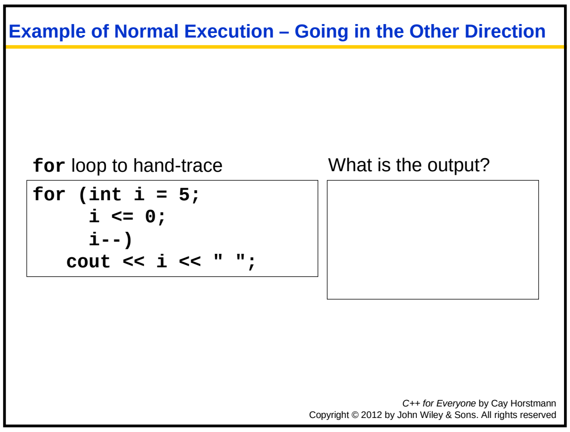
for loop

```
for (int i = 0;
     i <= 5;
     i++)
   cout << i << " ";
```

The output

```
0 1 2 3 4 5
```

Note that the output statement is
executed six times, not five

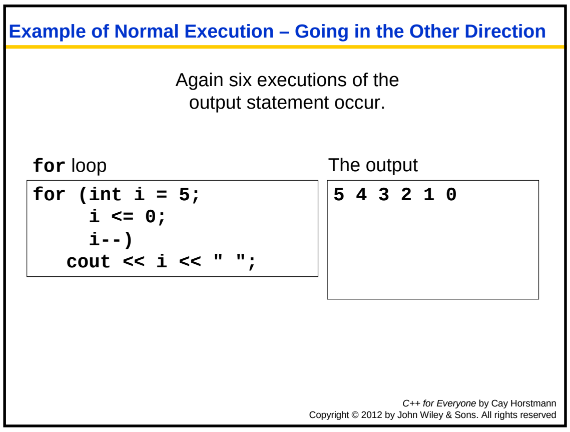


Example of Normal Execution – Going in the Other Direction

for loop to hand-trace

```
for (int i = 5;
     i <= 0;
     i--)
   cout << i << " ";
```

What is the output?



Example of Normal Execution – Going in the Other Direction

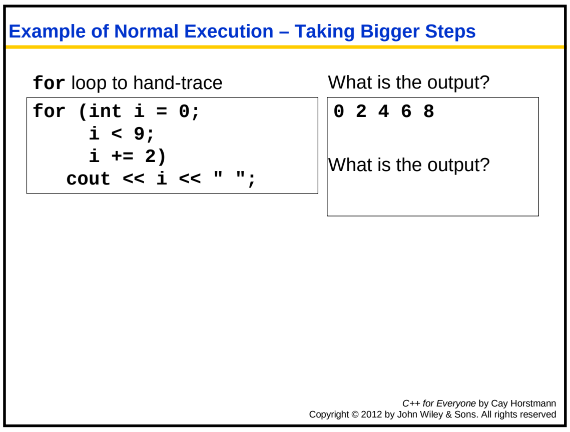
Again six executions of the
output statement occur.

for loop

```
for (int i = 5;
     i <= 0;
     i--)
   cout << i << " ";
```

The output

```
5 4 3 2 1 0
```



Example of Normal Execution – Taking Bigger Steps

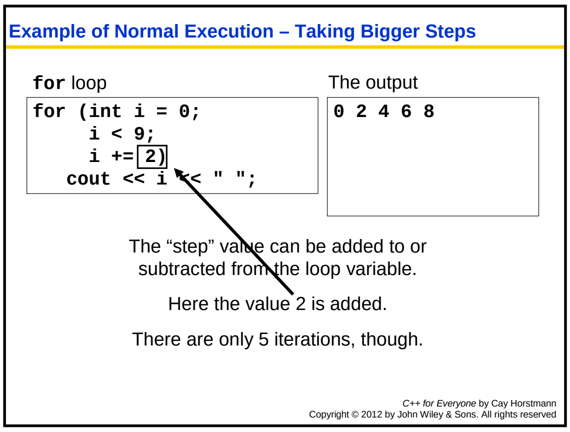
for loop to hand-trace

```
for (int i = 0;
     i < 9;
     i += 2)
   cout << i << " ";
```

What is the output?

```
0 2 4 6 8
```

What is the output?



Example of Normal Execution – Taking Bigger Steps

for loop

```
for (int i = 0;
     i < 9;
     i += 2)
   cout << i << " ";
```

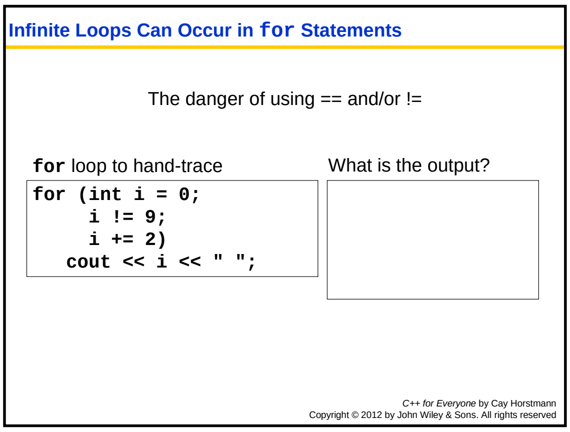
The output

```
0 2 4 6 8
```

The “step” value can be added to or
subtracted from the loop variable.

Here the value 2 is added.

There are only 5 iterations, though.



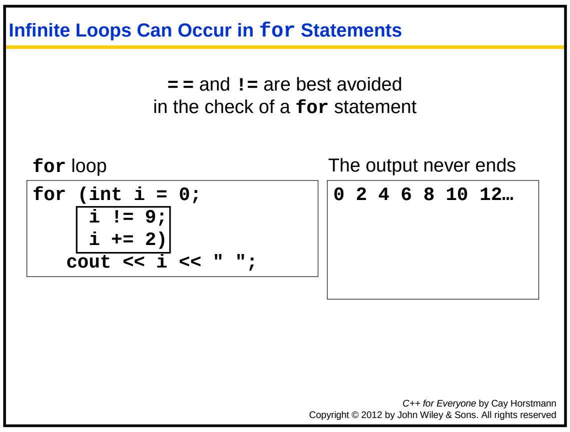
Infinite Loops Can Occur in `for` Statements

The danger of using == and/or !=

`for` loop to hand-trace

```
for (int i = 0;
     i != 9;
     i += 2)
   cout << i << " ";
```

What is the output?



Infinite Loops Can Occur in `for` Statements

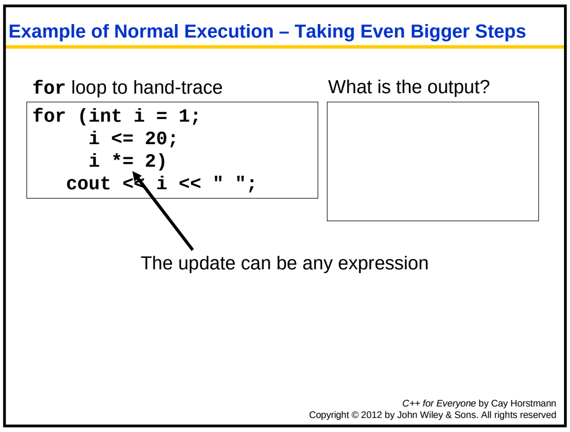
`==` and `!=` are best avoided
in the check of a `for` statement

`for` loop

```
for (int i = 0;
     i != 9;
     i += 2)
   cout << i << " ";
```

The output never ends

```
0 2 4 6 8 10 12…
```



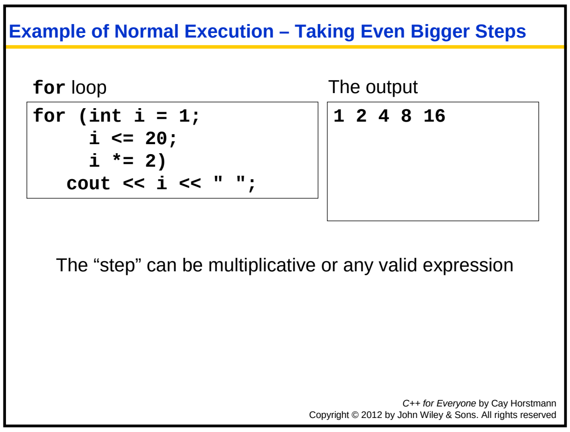
Example of Normal Execution – Taking Even Bigger Steps

`for` loop to hand-trace

```
for (int i = 1;
     i <= 20;
     i *= 2)
   cout << i << " ";
```

What is the output?

The update can be any expression



Example of Normal Execution – Taking Even Bigger Steps

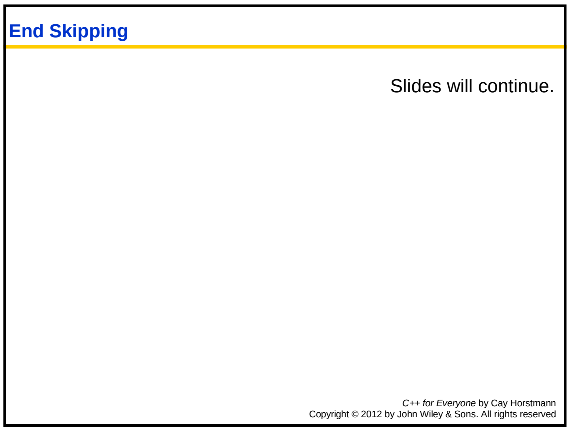
`for` loop

```
for (int i = 1;
     i <= 20;
     i *= 2)
   cout << i << " ";
```

The output

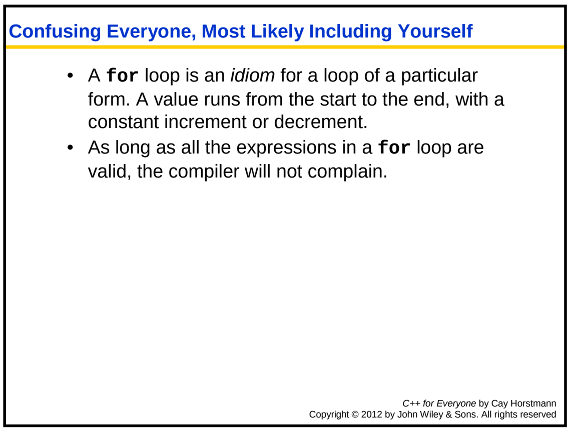
```
1 2 4 8 16
```

The “step” can be multiplicative or any valid expression



End Skipping

Slides will continue.



Confusing Everyone, Most Likely Including Yourself

- A **`for`** loop is an *idiom* for a loop of a particular form. A value runs from the start to the end, with a constant increment or decrement.
- As long as all the expressions in a **`for`** loop are valid, the compiler will not complain.

Confusing Everyone, Most Likely Including Yourself

A **for** loop should only be used to cause a loop variable to run, with a consistent increment, from the start to the end of a sequence of values.

Or you could write this (it works, but …)

```
for (cout << "Inputs: "; cin >> x; sum += x)
{
   count++;
}
```

Know Your Bounds – Symmetric vs. Asymmetric

- The start and end values should match the task the **for** loop is solving.
- The range 3 ≤ n ≤ 17 is *symmetric*, both end points are included so the **for** loop is:

```
for (int n = 3; n <= 17; n++)…
```

Know Your Bounds – Symmetric vs. Asymmetric

- When dealing with arrays (in a later chapter), you'll find that if there are N items in an array, you must deal with them using the range **[0..N).**
  So the **for** loop for arrays is:

```
for( int arrIndVar=0;
       arrIndVar<N;
       arrIndVar++ )…
```

- This still executes the statements N times.

  Many coders use this *asymmetric* form for ***every*** problem involving doing something *N* times.

How Many Times Was That?

Fence arithmetic

Don't forget to count the first (or last)
"post number" that a loop variable takes on.

Fence Arithmetic – Counting Iterations

- Finding the correct lower and upper bounds and the correct check for an iteration can be confusing.
  - Should you start at 0 or at 1?
  - Should you use **<= b** or **< b** as a termination condition?
- Counting the number of iterations is a very useful device for better understanding a loop.

Fence Arithmetic – Counting Iterations

Counting is <u>easier</u> for loops with *asymmetric* bounds.

The loop

```
for (i = a; i < b; i++)…
```

executes the statements **(b – a)** times and when a is 0: **b** times.

For example, the loop traversing the characters in a **string**,

```
for (i = 0; i < s.length(); i++)…
```

runs **s.length** times.

That makes perfect sense, since there are **s.length** characters in a **string**.

Fence Arithmetic Again – Counting Iterations

The loop with symmetric bounds,

```
for (i = a; i <= b; i++)…
```

is executed (b – a) + 1 times.

That "+1" is the source of many programming errors.

4.4 The do Loop

The **while** loop's condition test is the first thing that occurs in its execution.

The **do** loop (or **do-while** loop) has its condition tested only after at least one execution of the statements.

```
do
{
   statements
}
while (condition);
```

The do Loop

This means that the **do** loop should be used only when the statements must be executed before there is any knowledge of the condition.

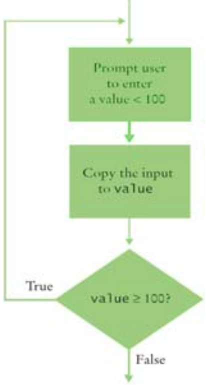
This also means that the **do** loop is the least used loop.

The do Loop

What problems require something to have happened before the testing in a loop?

Getting valid user input is often cited.

Here is the flowchart for the problem in which the user is supposed to enter a value less than 100 and processing must not continue until they do.



The do Loop

Here is the code:

```
int value;
do
{
   cout << "Enter a value < 100: ";
   cin >> value;
}
while (value >= 100);
```

In this form, the user sees the same prompt each time until the enter valid input.

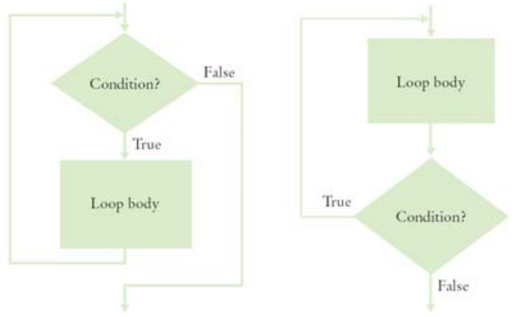
The do Loop

In order to have a different, "error" prompt that the user sees only on *invalid* input, the initial prompt and input would be before a **while** loop:

```
int value;
cout << "Enter a value < 100:";
while (value >= 100);
{
   cout << "Sorry, that is larger than 100\n"
        << "Try again: ";
   cin >> value;
}
```

Notice what happens when the user gives valid input on the first attempt: nothing – good.

Flowcharts for the `while` Loop and the `do` Loop



4.5 Processing Input – When and/or How to Stop?

When and/or
how to stop?

Processing Input – When and/or How to Stop?

or be stopped!

Processing Input – When and/or How to Stop?

- We need to know, when getting input from a user, when they are done.
- One method is to hire a sentinel (as shown)

  or more correctly choose a *value* whose meaning is STOP!
- As long as there is a known range of valid data points, we can use a value not in it.

Processing Input – When and/or How to Stop?

- We will write code to calculate the average of some salary values input by the user.

  How many will there be?

  That is the problem. We can’t know.

  But we can use a *sentinel value*, as long as we tell the user to use it, to tell us when they are done.

- Since salaries are never negative, we can safely choose -1 as our sentinel value.

Processing Input – When and/or How to Stop?

- In order to have a value to test, we will need to get the first input before the loop. The loop statements will process each non-sentinel value, and then get the next input.
- Suppose the user entered the sentinel value as the first input. Because averages involve division by the count of the inputs, we need to protect against dividing by zero. Using an **`if-else`** statement from Chapter 3 will do.

The Complete Salary Average Program

ch04/sentinel.cpp

```
#include <iostream>
using namespace std;

int main()
{
   double sum = 0;
   int count = 0;
   double salary = 0;
   // get all the inputs
   cout << "Enter salaries, -1 to finish: ";
   while (salary != -1)
   {
      cin >> salary;
      if (salary != –1)
      {
         sum = sum + salary;
         count++;
      }
   }
```

The Complete Salary Average Program

```
   // process and display the average
   if (count > 0)
   {
      double average = sum / count;
      cout << "Average salary: " << average << endl;
   }
   else
   {
      cout << "No data" << endl;
   }

   return 0;
}
```

A program run:

```
Enter salaries, -1 to finish: 10 10 40 -1
Average salary: 20
```

Using Failed Input for Processing

- Sometimes it is easier and a bit more intuitive to ask the user to “Hit Q to Quit” instead or requiring the input of a sentinel value.
- Sometimes picking a sentinel value is simply impossible – if any valid number is allowed, which number could be chosen?

Using Failed Input for Processing

- In the previous chapter, we used **`cin.fail()`** to test if the most recent input failed.
- Note that if you intend to take more input from the keyboard after using failed input to end a loop, you must reset the keyboard with **`cin.clear()`**.

Using Failed Input for Processing

If we introduce a bool variable to be used to test for a failed input, we can use **`cin.fail()`** to test for the input of a ‘Q’ when we were expecting a number:

Using Failed Input for Processing

```
cout << "Enter values, Q to quit: ";
bool more = true;
while (more)
{
   cin >> value;
   if (cin.fail())
   {
      more = false;
   }
   else
   {
      // process value here
   }
}
cin.clear() // reset if more input is to be taken
```

Using Failed Input for Processing

- Using a **`bool`** variable in this way is disliked by many programmers.

  Why?

- **`cin.fail`** is set *when* **`>>`** fails
  It is not really a top or bottom test.

  If only we could use the input itself to control the loop – we can!

- An input that does not succeed is considered to be **`false`** so it can be used in the **`while`**'s test.

Using Failed Input for Processing

Using the input attempt directly we have:

```
cout << "Enter values, Q to quit: ";
while (cin >> value)
{
   // process value here
}
cin.clear();
```

The Loop and a Half Problem and the `break` Statement

Those same programmers who dislike loops that are controlled by a **`bool`** variable have another reason: the actual test for loop termination is in the *middle* of the loop. Again it is not really a top or bottom test.

This is called a loop-and-a-half.

The Loop and a Half Problem and the `break` Statement

If we test for a failed read, we can stop the loop *at that point*:

```
while (true)
{
   cin >> value;
   if (cin.fail()) { break; }
   // process value here
}
cin.clear() // reset if more input is to be taken
```

The **`break`** statement breaks out of the enclosing loop, independent of the loop condition.

4.6 Problem Solving: Storyboards

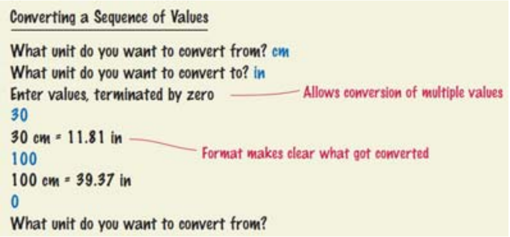
- One useful problem solving technique is the use of storyboards to model user interaction. It can help answer:

  - What information does the user provide, and in which order?
  - What information will your program display, and in which format?
  - What should happen when there is an error?
  - When does the program quit?

A storyboard consists of annotated sketches for each step in an action sequence.

Storyboard Example

- Goal: Converting a sequence of values
  - Will require a loop and some variables
  - Handle one conversion each time through the loop



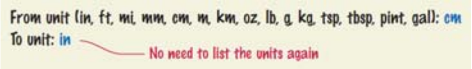
Converting a Sequence of Values

```
What unit do you want to convert from? cm
What unit do you want to convert to? in
Enter values, terminated by zero
30
30 cm = 11.81 in
100
100 cm = 39.37 in
0
What unit do you want to convert from?
```

Allows conversion of multiple values
Format makes clear what got converted

What can go wrong?

- Unknown unit types
  - How do you spell centimeters and inches?
  - What other conversions are available?
  - Solution:
    - Show a list of the acceptable unit types

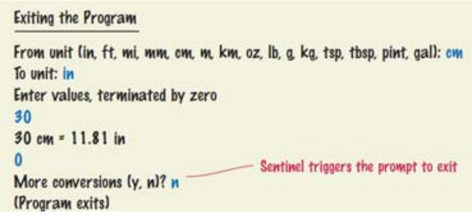


```
From unit (in, ft, mi, mm, cm, m, km, oz, lb, g, kg, tsp, tbsp, pint, gal): cm
To unit: in
```

No need to list the units again

What else can go wrong?

- How does the user quit the program?



Exiting the Program

```
From unit (in, ft, mi, mm, cm, m, km, oz, lb, g, kg, tsp, tbsp, pint, gal): cm
To unit: in
Enter values, terminated by zero
30
30 cm = 11.81 in
0
More conversions (y, n)? n
(Program exits)
```

Sentinel triggers the prompt to exit

- Storyboards help you plan a program
  - Knowing the flow helps you structure your code

4.7 Common Loop Algorithms

1: Sum and Average Value
2: Counting Matches
3: Finding the First Match
4: Maximum and Minimum
5: Comparing Adjacent Values

Sum and Average Examples

```
double total = 0;
double input;
while (cin >> input)
{
   total = total + input;
}
```

- Sum of Values
  - Initialize total to 0
  - Use `while` loop with sentinel

- Average of Values
  - Use Sum of Values
  - Initialize count to 0
    - Increment per input
  - Check for count 0
    - Before divide!

```
double total = 0;
int count = 0;
double input;
while (cin >> input)
{
   total = total + input;
   count++;
}
double average = 0;
if (count > 0)
  { average = total / count; }
```

Counting Matches

- Counting Matches
  - Initialize count to 0
  - Use a `for` loop
  - Add to count per match

```
int short_words = 0;
string input;
while (cin >> input)
{
   if (input.length() <= 3)
   {
      short_words++;
   }
}
```

Finding the First Match

```
bool found = false;
int position = 0;
while (!found &&
       position < str.length())
{
   string ch = str.substr
     (position, 1);
   if (ch == " ") { found = true; }
   else { position++; }
}
```

- Initialize `boolean` sentinel to `false`
- Initialize position counter to 0
- Use a compound conditional in loop

A pre-test loop (while or for) will handle the case where the string is empty!

Prompt Until a Match is Found

```
bool valid = false;
double input;
while (!valid)
{
   cout << "Please enter a positive value < 100: ";
   cin >> input;
   if (0 < input && input < 100) { valid = true; }
   else { cout << "Invalid input." << endl; }
}
```

- Initialize `boolean` flag to `false`
- Test sentinel in `while` loop
  - Get input, and compare to range
    - If input is in range, change flag to true
    - Loop will stop executing

Maximum and Minimum

```
double largest;
cin >> largest;
double input;
while (cin >> input)
{
   if (input > largest)
   {
      largest = input;
   }
}
```

```
double smallest;
cin >> smallest;
double input;
while (cin >> input)
{
   if (input < smallest)
   {
      smallest = input;
   }
}
```

- Get first input value
  - This is the largest (or smallest) that you have seen so far!
- Loop `while` you have a valid number (non-sentinel)
  - Get another input value
  - Compare new input to largest (or smallest)
  - Update largest (or smallest) if necessary

Comparing Adjacent Values

```
double input;
double previous;
cin >> previous;
while (cin >> input)
{
   if (input == previous) { cout <<
         "Duplicate input" << endl; }
   previous = input;
}
```

- Get first input value
- Use `while` to determine if there are more to check
  - Copy input to previous variable
  - Get next value into input variable
  - Compare input to previous, and output if same

4.8 Nested Loops

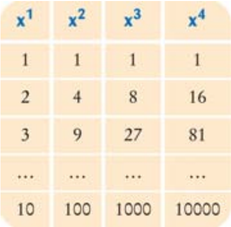
For each hour, 60 minutes are processed – a nested loop.

Nested Loops

- Nested loops are used mostly for data in tables as rows and columns.
- The processing across the columns is a loop, as you have seen before, "nested" inside a loop for going down the rows.
- Each row is processed similarly so design begins at that level. After writing a loop to process a generalized row, that loop, called the "inner loop," is placed inside an "outer loop."

Nested Loops

Write a program to produce a table of powers.
The output should be something like this:



x^1	x^2	x^3	x^4
1	1	1	1
2	4	8	16
3	9	27	81
...	...	...	...
10	100	1000	10000

Nested Loops

- The first step is to solve the “nested” loop.
- There are four columns and in each column we display the power. Using x to be the number of the row we are processing, we have (in pseudo-code):

```
for n from 1 to 4
{
    print $x^n$
}
```

- You would test that this works in your code before continuing. If you can’t correctly print one row, why try printing lots of them?

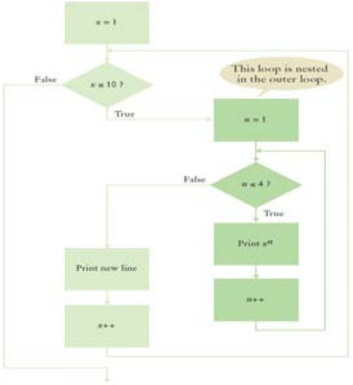
Nested Loops

Now, putting the inner loop into the whole process we have:

(don’t forget to indent, nestedly)

```
print table header
for x from 1 to 10
{
    print table row
    print endl
}
```

Nested Loops



The Complete Program for Table of Powers

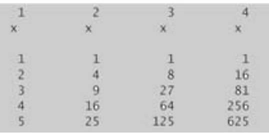
ch04/powtable.cpp

```
#include <iostream>
#include <iomanip>
#include <cmath>
using namespace std;

int main()
{
   const int NMAX = 4;
   const double XMAX = 10;

   // Print table header
   for (int n = 1; n <= NMAX; n++)
   {
      cout << setw(10) << n;
   }
   cout << endl;
   for (int n = 1; n <= NMAX; n++)
   {
      cout << setw(10) << "x ";
   }
   cout << endl << endl;
```

The Complete Program for Table of Powers

```
      // Print table body
      for (double x = 1; x <= XMAX; x++)
      {
         // Print table row
         for (int n = 1; n <= NMAX; n++)
         {
            cout << setw(10) << pow(x, n);
         }
         cout << endl;
      }

      return 0;
   }
```

The program run would be:



```
  1          2          3          4
 x          x          x          x

  1          1          1          1
  2          4          8         16
  3          9         27         81
  4         16         64        256
  5         25        125        625
```

More Nested Loop Examples

The loop variables can have a value relationship. In this example the inner loop depends on the value of the outer loop.

```
for (i = 1; i <= 4; i++)
   for (j = 1; j <= i; j++)
      cout << "*";
cout << endl;
```

The output will be:

```
*
**
***
****
```

More Nested Loop Examples

```
for (i = 1; i <= 4; i++)
   for (j = 1; j <= i; j++)
      cout << "*";
cout << endl;
```

j is *each* line's length, which is different for each line, and depends on the current line number, **i**

```
*
* *
* * *
* * * *
```

i represents the row number or the line number

More Nested Loop Examples

```
for (i = 1; i <= 4; i++)
   for (j = 1; j <= i; j++)
      cout << "*";
cout << endl;
```

j is *each* line's length, which is different for each line, and depends on the current line number, **i**

```
j stops at: i
            1

when i is: i 1
```

i represents the row number or the line number

More Nested Loop Examples

```
for (i = 1; i <= 4; i++)
   for (j = 1; j <= i; j++)
      cout << "*";
cout << endl;
```

j is *each* line's length, which is different for each line, and depends on the current line number, **i**

```
j stops at: i
            1

when i is: i 1   *
```

i represents the row number or the line number

More Nested Loop Examples

```
for (i = 1; i <= 4; i++)
   for (j = 1; j <= i; j++)
      cout << "*";
cout << endl;
```

j is *each* line's length, which is different for each line. and depends on the current line number, **i**

```
j stops at: i
            1

when i is: i 1   *
           i 2   * *
```

i represents the row number or the line number

More Nested Loop Examples

```
for (i = 1; i <= 4; i++)
   for (j = 1; j <= i; j++)
      cout << "*";
cout << endl;
```

j is *each* line's length, which is different for each line, and depends on the current line number, **i**

```
j stops at: i i i
            1 2 3

when i is: i 1   *
           i 2   * *
           i 3   * * *
```

i represents the row number or the line number

More Nested Loop Examples

```
for (i = 1; i <= 4; i++)
   for (j = 1; j <= i; j++)
      cout << "*";
cout << endl;
```

j is *each* line's length, which is different for each line, and depends on the current line number, **i**

```
j stops at: i i i i
            1 2 3 4

when i is: i 1   *
           i 2   * *
           i 3   * * *
           i 4   * * * *
```

i represents the row number or the line number

More Nested Loop Examples

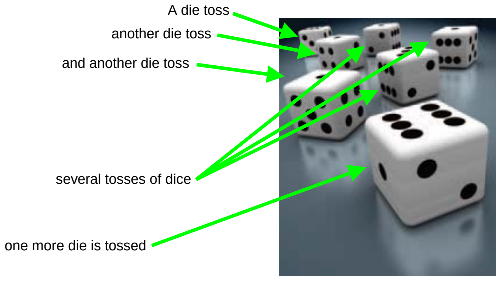
In this example, the loop variables are still related, but the processing is a bit more complicated.

```
for (i = 1; i <= 3; i++)
{
   for (j = 1; j <= 5; j++)
   {
      if (i + j % 2 == 0) { cout << "*"; }
      else { cout << " "; }
   }
   cout << endl;
}
```

The output will be:

```
* * *
 * *
* * *
```

4.9 Random Numbers and Simulations



was that an English lesson?

Simulations

A *simulation program* uses the computer to simulate an activity in the real world (or in an imaginary one).

Simulations

- Simulations are commonly used for
  - Predicting climate change
  - Analyzing traffic
  - Picking stocks
  - Many other applications in science and business

Randomness for Reality (Simulating)

- Programmers must model the “real world” at times.
- Consider the problem of modeling customers arriving at a store.

Do we know the rate?

Does anyone?

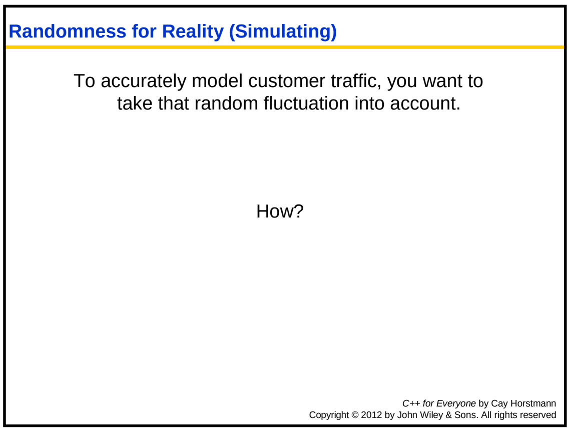
How about the shopkeeper!

Randomness for Reality (Simulating)

Ask the shopkeeper:

It’s about every five minutes
…or so…
…give or a take a couple…
…or three…

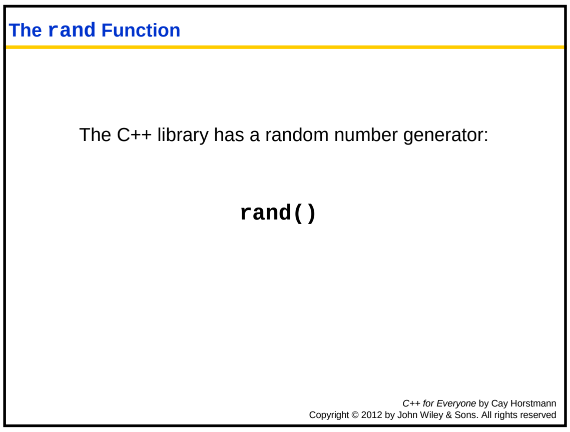
…but on certain Tuesdays…



Randomness for Reality (Simulating)

To accurately model customer traffic, you want to take that random fluctuation into account.

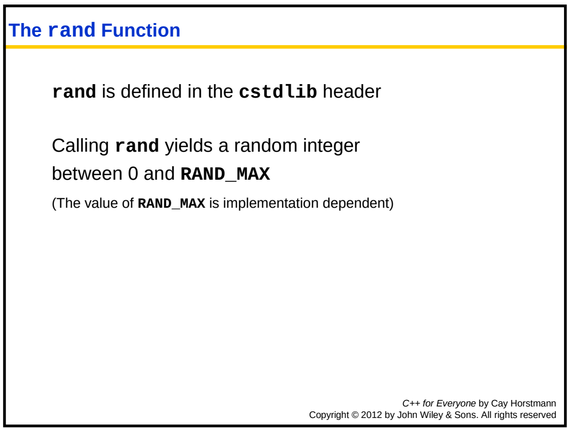
How?



The `rand` Function

The C++ library has a random number generator:

`rand()`

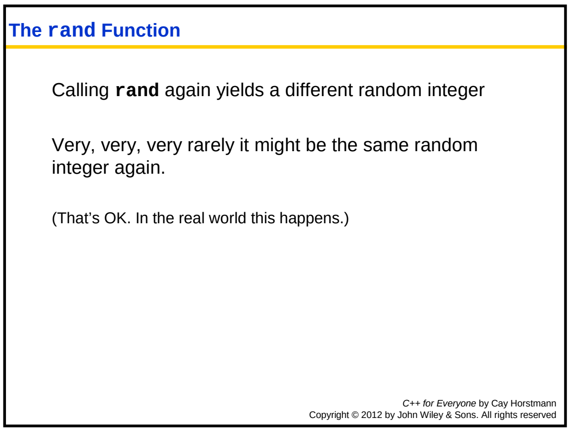


The `rand` Function

`rand` is defined in the **`cstdlib`** header

Calling **`rand`** yields a random integer between 0 and **`RAND_MAX`**

(The value of **`RAND_MAX`** is implementation dependent)

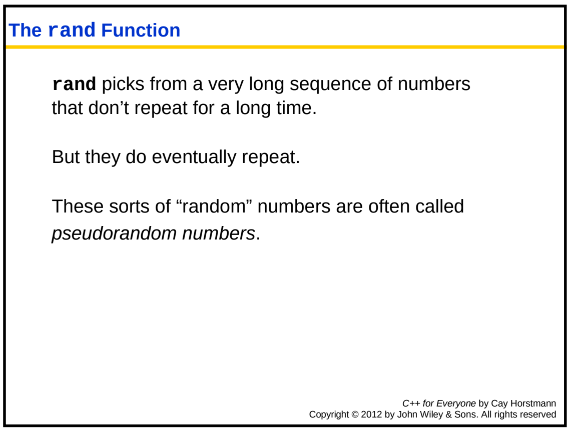


The `rand` Function

Calling **`rand`** again yields a different random integer

Very, very, very rarely it might be the same random integer again.

(That’s OK. In the real world this happens.)

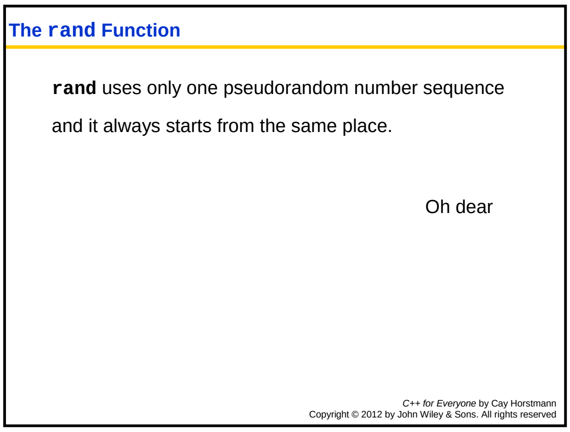


The `rand` Function

`rand` picks from a very long sequence of numbers that don’t repeat for a long time.

But they do eventually repeat.

These sorts of “random” numbers are often called *pseudorandom numbers*.



The `rand` Function

`rand` uses only one pseudorandom number sequence

and it always starts from the same place.

Oh dear

The `rand` Function

When you run your program again on another day,
the call to **`rand`** will start with:

*the **same** random number!*

Is it very “real world” to use the same sequence
over and over?

No, but it’s really nice for testing purposes.

but…

Seeding the `rand` Function

You can “seed” the random generator to indicate
where it should start in the pseudorandom sequence

Calling **`srand`** sets where **`rand`** starts

`srand` is defined in the **`cstdlib`** header

Seeding the `rand` Function

But what value would be different every *time*
you run your program?

(hint)

How about the time?

Seeding the `rand` Function

You can obtain the system time.

Calling **`time(0)`** gets the current time

Note the zero. It is required.

`time` is defined in the **`time`** header

Seeding the `rand` Function

Calling **`srand`** sets where **`rand`** starts.

Calling **`time(0)`** gets the current time.

So, to set up for “really, really random”
random numbers on each program run:

```
srand(time(0)); // seed rand()
```

(Well, as “really random” as we can hope for.)

Modeling Using the `rand` Function

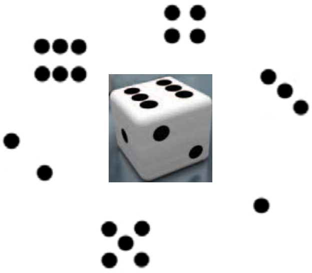
Let’s model a pair of dice,

Modeling Using the `rand` Function

one die at a time.

Modeling Using the `rand` Function

What are the numbers on one die?



Modeling Using the `rand` Function

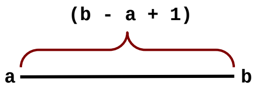
Numbers we can work with please!

Modeling Using the `rand` Function

What are the bounds of the range of numbers on one die?
1 and 6 (inclusive)

We want a value randomly between those endpoints (inclusively)

Modeling Using the `rand` Function

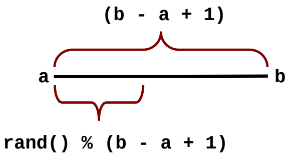


Given two endpoints,
a and **b**, recall there are

`(b - a + 1)`

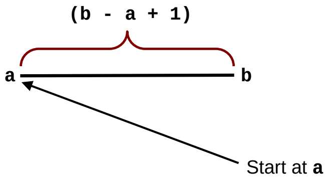
values between **a** and **b**,
(including the bounds themselves).

Modeling Using the `rand` Function



Obtain a random value
between **`0`** and **`b – a`**
by using the **`rand()`** function

Modeling Using the `rand` Function

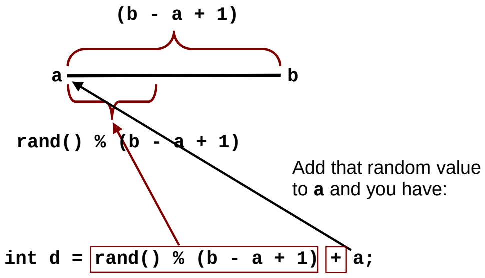


`(b - a + 1)`

a **b**

Start at **a**

Modeling Using the `rand` Function



`(b - a + 1)`

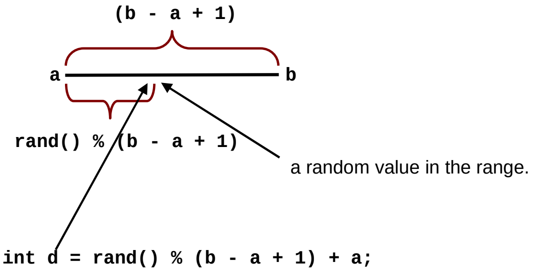
a **b**

`rand() % (b - a + 1)`

Add that random value
to **a** and you have:

`int d = rand() % (b - a + 1) + a;`

Modeling Using the `rand` Function



`(b - a + 1)`

a **b**

`rand() % (b - a + 1)`

a random value in the range.

`int d = rand() % (b - a + 1) + a;`

Modeling Using the `rand` Function

Using 1 and 6 as the bounds
and
modeling for two dice,
running for 10 tries,

we have:

Modeling Using the `rand` Function

ch04/dice.cpp

```
#include <iostream>
#include <string>
#include <cstdlib>
#include <ctime>
using namespace std;

int main()
{
   srand(time(0));

   for (i = 1; i <= 10; i++)
   {
      int d1 = rand() % 6 + 1;
      int d2 = rand() % 6 + 1;
      cout << d1 << " " << d2 << endl;
   }
   cout << endl;
   return 0;
}
```

One of many different
Program Runs:

```
5 1
2 1
1 2
5 1
1 2
6 4
4 4
6 1
6 3
5 2
```

The Monte Carlo Method

The premier gaming "*table d'darts*"
at one of the less well known casinos in Monte Carlo,
somewhat close but not quite next door to Le Grand Casino.

The Monte Carlo Method

As long as we're here, let's go in!

The Monte Carlo Method

The Monte Carlo method is a method for finding approximate solutions to problems that cannot be precisely solved.

Here is an example: compute π

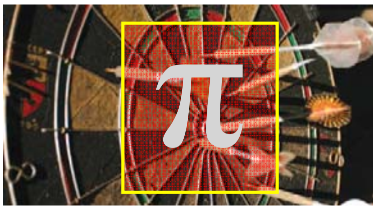
This is difficult.

The Monte Carlo Method

While we are in this fine casino,
we should at least play one game at the "*table d'darts"*

The Monte Carlo Method

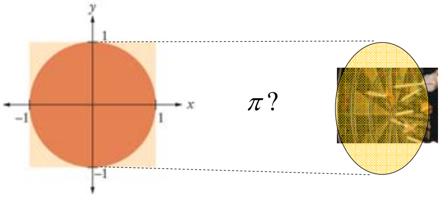
THAT'S IT!



By shooting darts (and a little math)
we can obtain an approximation for π.

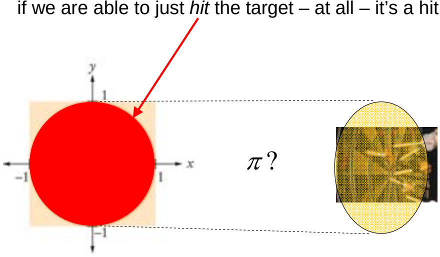
The Monte Carlo Method

Consider placing the round dartboard
inside an exactly fitting square



The Monte Carlo Method

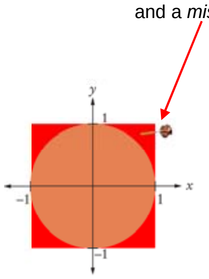
As we toss darts at the target,
if we are able to just *hit* the target – at all – it's a hit.



(no wonder this is such a pathetic casino)

The Monte Carlo Method

and a *miss* is a miss.

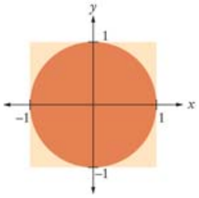


π ?

The Monte Carlo Method

The **(x,y)** coordinate of a *hit* is when (**x**^{2} **+ y**$^{2)}$ **≤ 1**.
In code:

```
if (x * x + y * y <= 1) { hits++; }
```



The Monte Carlo Method

Our coded random shots will give a ratio of
hits/tries
that is approximately equal to the ratio of
the areas of the circle and the square:

π/4

The Monte Carlo Method

Multiply by 4 and we have an estimate for π!

```
π = 4 * hits/tries;
```

The longer we run our program,
the more random numbers we generate,
the better the estimate.

The Monte Carlo Method

For the **x** and **y** coordinates within the circle,
we need random **x** and **y** values between **-1** and **1**.

That's a range of (**-1 + 1 + 1)** or **2.**

As before, we want to add some random portion
of this range to the low endpoint, **-1**.

But we will want a floating point value, not an integer.

The Monte Carlo Method

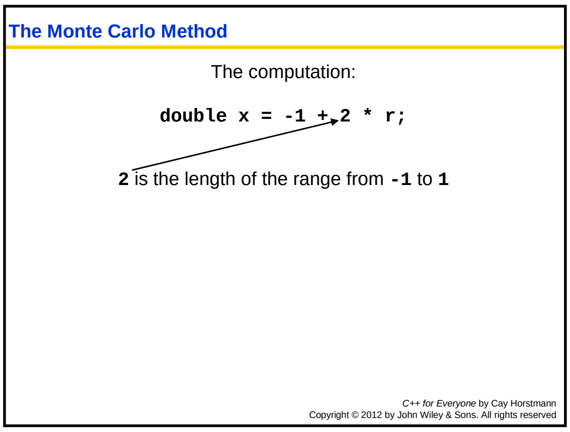
We must use **rand** with **double** values
to obtain that random portion.

```
double r = rand() * 1.0 / RAND_MAX;
```

The value **r** is a random floating-point
value between 0 and 1.

You can think of this as a percentage if you like.

(Use **1.0** to make the **/** operator not do integer division)

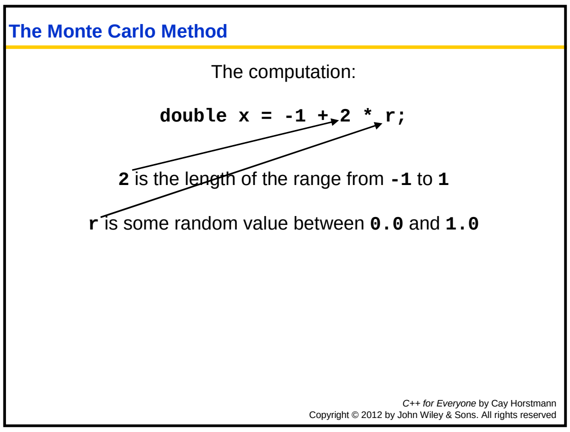


The Monte Carlo Method

The computation:

`double x = -1 + 2 * r;`

`2` is the length of the range from `-1` to `1`



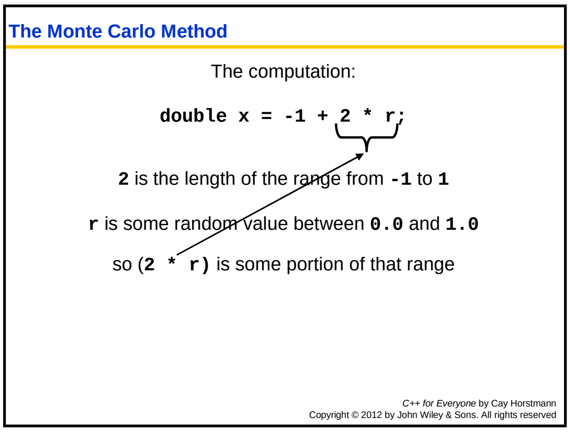
The Monte Carlo Method

The computation:

`double x = -1 + 2 * r;`

`2` is the length of the range from `-1` to `1`

`r` is some random value between `0.0` and `1.0`



The Monte Carlo Method

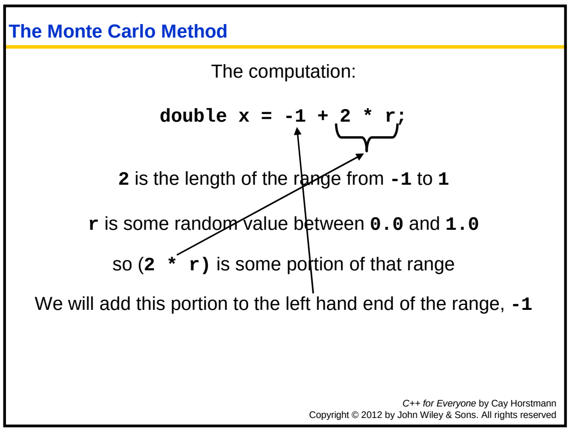
The computation:

`double x = -1 + 2 * r;`

`2` is the length of the range from `-1` to `1`

`r` is some random value between `0.0` and `1.0`

so (`2 * r)` is some portion of that range



The Monte Carlo Method

The computation:

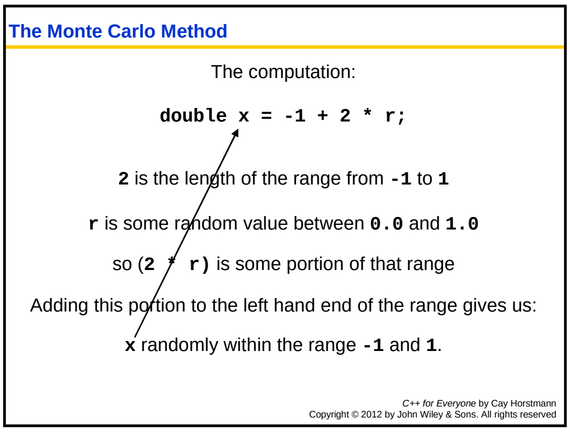
`double x = -1 + 2 * r;`

`2` is the length of the range from `-1` to `1`

`r` is some random value between `0.0` and `1.0`

so (`2 * r)` is some portion of that range

We will add this portion to the left hand end of the range, `-1`



The Monte Carlo Method

The computation:

`double x = -1 + 2 * r;`

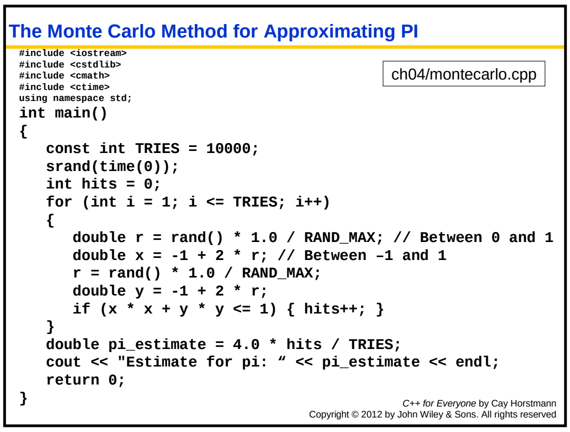
`2` is the length of the range from `-1` to `1`

`r` is some random value between `0.0` and `1.0`

so (`2 * r)` is some portion of that range

Adding this portion to the left hand end of the range gives us:

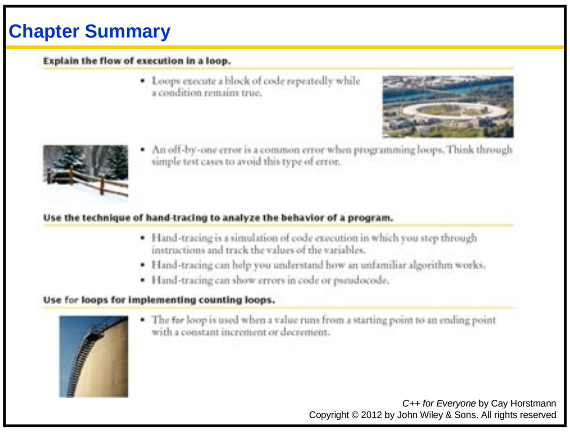
`x` randomly within the range `-1` and `1`.



The Monte Carlo Method for Approximating PI

ch04/montecarlo.cpp

```
#include <iostream>
#include <cstdlib>
#include <cmath>
#include <ctime>
using namespace std;
int main()
{
   const int TRIES = 10000;
   srand(time(0));
   int hits = 0;
   for (int i = 1; i <= TRIES; i++)
   {
      double r = rand() * 1.0 / RAND_MAX; // Between 0 and 1
      double x = -1 + 2 * r; // Between –1 and 1
      r = rand() * 1.0 / RAND_MAX;
      double y = -1 + 2 * r;
      if (x * x + y * y <= 1) { hits++; }
   }
   double pi_estimate = 4.0 * hits / TRIES;
   cout << "Estimate for pi: “ << pi_estimate << endl;
   return 0;
}
```



Chapter Summary

Explain the flow of execution in a loop.

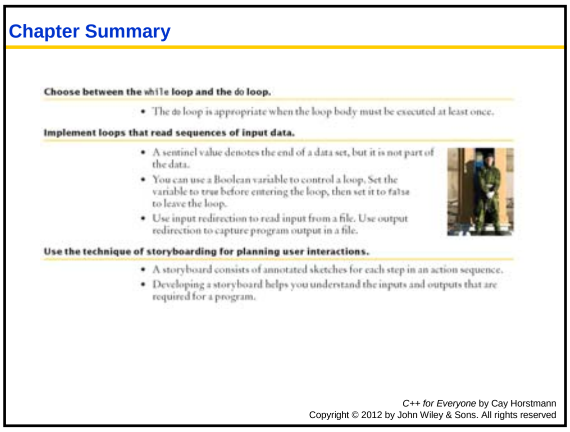
- Loops execute a block of code repeatedly while a condition remains true.
- An off-by-one error is a common error when programming loops. Think through simple test cases to avoid this type of error.

Use the technique of hand-tracing to analyze the behavior of a program.

- Hand-tracing is a simulation of code execution in which you step through instructions and track the values of the variables.
- Hand-tracing can help you understand how an unfamiliar algorithm works.
- Hand-tracing can show errors in code or pseudocode.

Use `for` loops for implementing counting loops.

- The `for` loop is used when a value runs from a starting point to an ending point with a constant increment or decrement.



Chapter Summary

Choose between the `while` loop and the `do` loop.

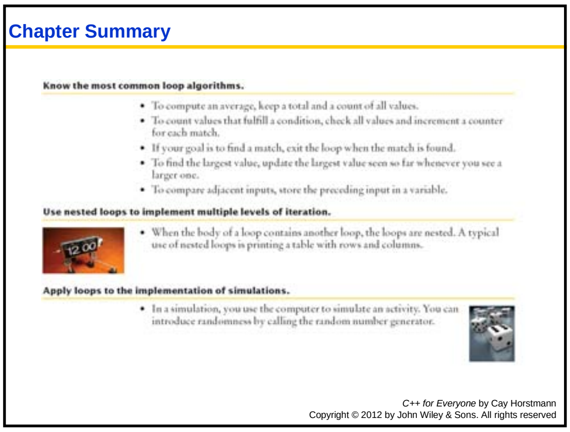
- The `do` loop is appropriate when the loop body must be executed at least once.

Implement loops that read sequences of input data.

- A sentinel value denotes the end of a data set, but it is not part of the data.
- You can use a Boolean variable to control a loop. Set the variable to `true` before entering the loop, then set it to `false` to leave the loop.
- Use input redirection to read input from a file. Use output redirection to capture program output in a file.

Use the technique of storyboarding for planning user interactions.

- A storyboard consists of annotated sketches for each step in an action sequence.
- Developing a storyboard helps you understand the inputs and outputs that are required for a program.



Chapter Summary

Know the most common loop algorithms.

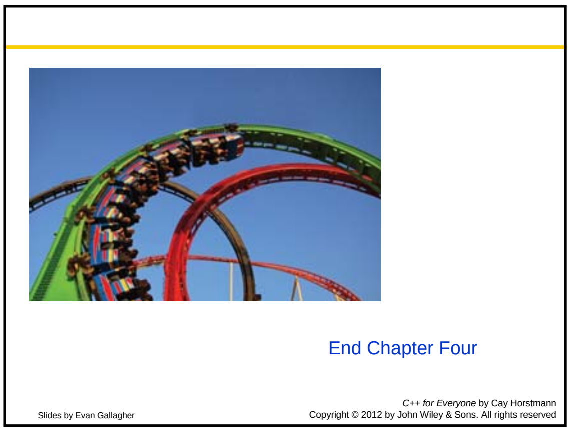
- To compute an average, keep a total and a count of all values.
- To count values that fulfill a condition, check all values and increment a counter for each match.
- If your goal is to find a match, exit the loop when the match is found.
- To find the largest value, update the largest value seen so far whenever you see a larger one.
- To compare adjacent inputs, store the preceding input in a variable.

Use nested loops to implement multiple levels of iteration.

- When the body of a loop contains another loop, the loops are nested. A typical use of nested loops is printing a table with rows and columns.

Apply loops to the implementation of simulations.

- In a simulation, you use the computer to simulate an activity. You can introduce randomness by calling the random number generator.



End Chapter Four

Slides by Evan Gallagher