SWEN 6301 Software Construction

Lecture 9: Code Tuning Strategies and Techniques

Outline

- Logic
- Loops
- Data Transformations
- Expressions

Logic

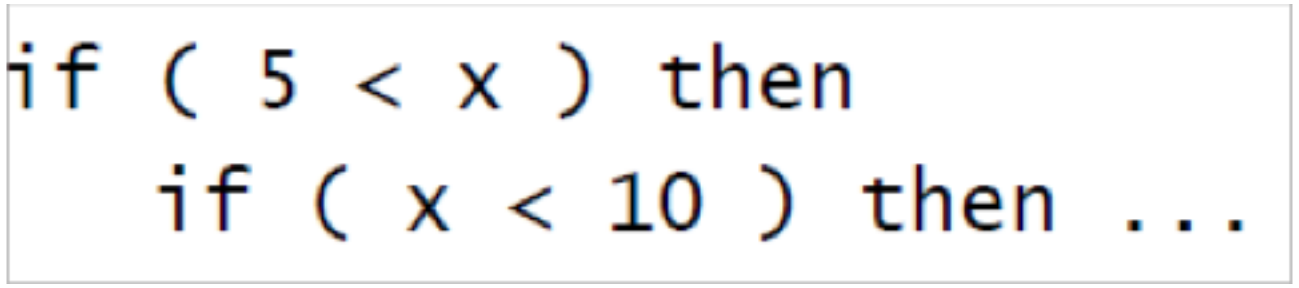
- Suppose you have a statement like

```
if ( 5 < x ) and ( x < 10 ) then ...
```

- Once you've determined that *x* is not greater than 5, you don't need to perform the second half of the test.
- Some languages provide a form of expression evaluation known as "short-circuit evaluation," which means that the compiler generates code that automatically stops testing as soon as it knows the answer.
- **If not, how to fix it?**

Logic

- **Stop Testing When You Know the Answer**
- If your language doesn’t support short-circuit evaluation natively, you have to avoid using *and* and *or*, adding logic instead. With short-circuit evaluation, the code above changes to this:



```
if ( 5 < x ) then
   if ( x < 10 ) then ...
```

Logic

- **Any problem?**

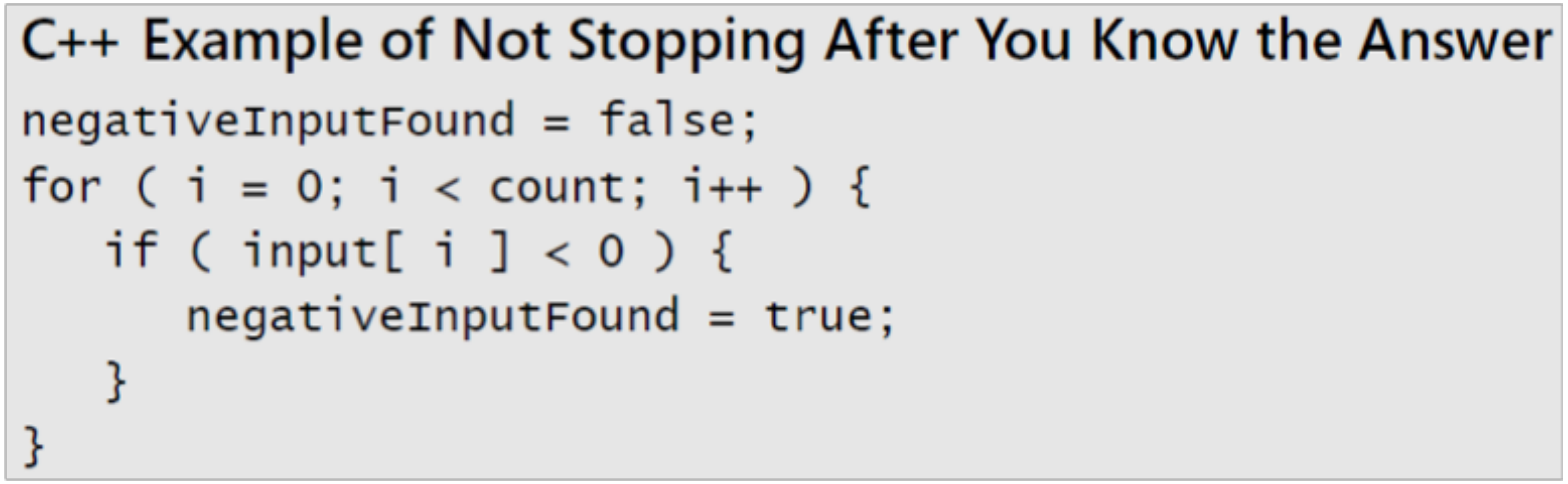
```
negativeInputFound = false;
for ( i = 0; i < count; i++ ) {
    if ( input[ i ] < 0 ) {
        negativeInputFound = true;
    }
}
```

Logic

- **Stop Testing When You Know the Answer**
- The principle of not testing after you know the answer is a good one for many other kinds of cases as well.
  - A search loop is a common case.
- If you're scanning an array of input numbers for a negative value and you simply need to know whether a negative value is present, one approach is to check every value, setting a ***negativeFound*** variable when you find one.

Logic

- **Stop Testing When You Know the Answer**
- Here’s how the search loop would look:



C++ Example of Not Stopping After You Know the Answer

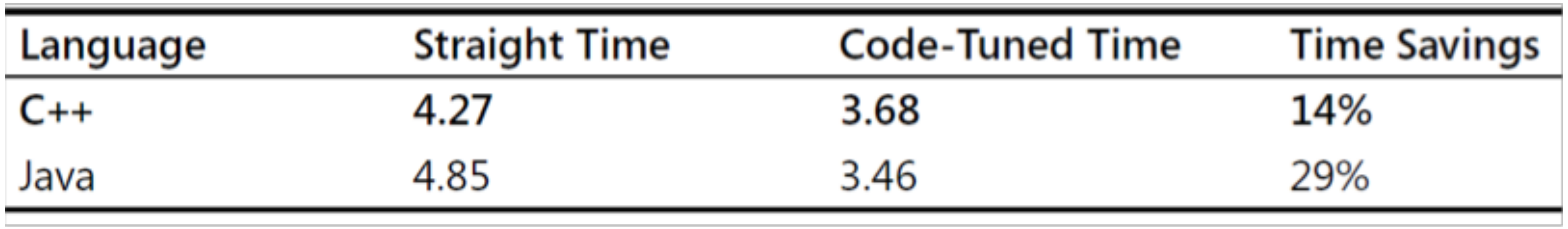
```
negativeInputFound = false;
for ( i = 0; i < count; i++ ) {
   if ( input[ i ] < 0 ) {
      negativeInputFound = true;
   }
}
```

Logic

- **Stop Testing When You Know the Answer**
- A better approach would be to stop scanning as soon as you find a negative value. Any of these approaches would solve the problem:
  - Add a *break* statement after the *negativeInputFound = true* line.
  - If your language doesn't have *break*, emulate a *break* with a *goto* that goes to the first statement after the loop.
  - Change the *for* loop to a *while* loop, and check for *negativeInputFound* as well as for incrementing the loop counter past *count*.
  - Change the *for* loop to a *while* loop, put a sentinel value in the first array element after the last value entry, and simply check for a negative value in the *while* test.
  - After the loop terminates, see whether the position of the first found value is in the array or one past the end.

Logic

- **Stop Testing When You Know the Answer**
- Here are the results of using the *break* keyword in C++ and Java:



Language	Straight Time	Code-Tuned Time	Time Savings
C++	4.27	3.68	14%
Java	4.85	3.46	29%

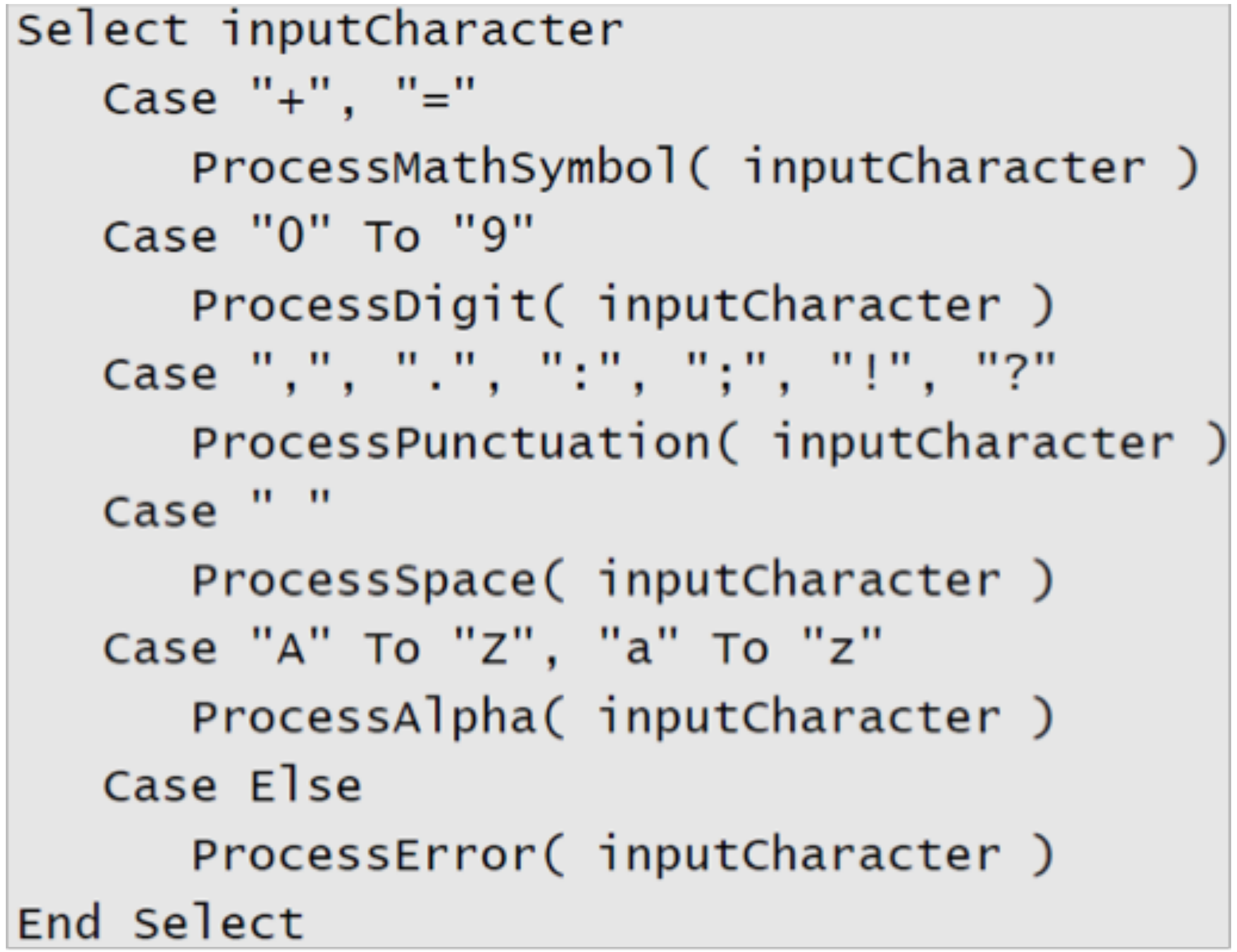
- The impact of this change varies a great deal depending on how many values you have and how often you expect to find a negative value. This test assumed an average of 100 values and assumed that a negative value would be found 50 percent of the time.

Logic

- **Order Tests by Frequency**
- *Arrange tests so that the one that’s fastest and most likely to be true* is performed first.
- It should be easy to drop through the normal case, and if there are inefficiencies, they should be in processing the uncommon cases. This principle applies to *case* statements and to chains of *if-then-else*s.

Logic

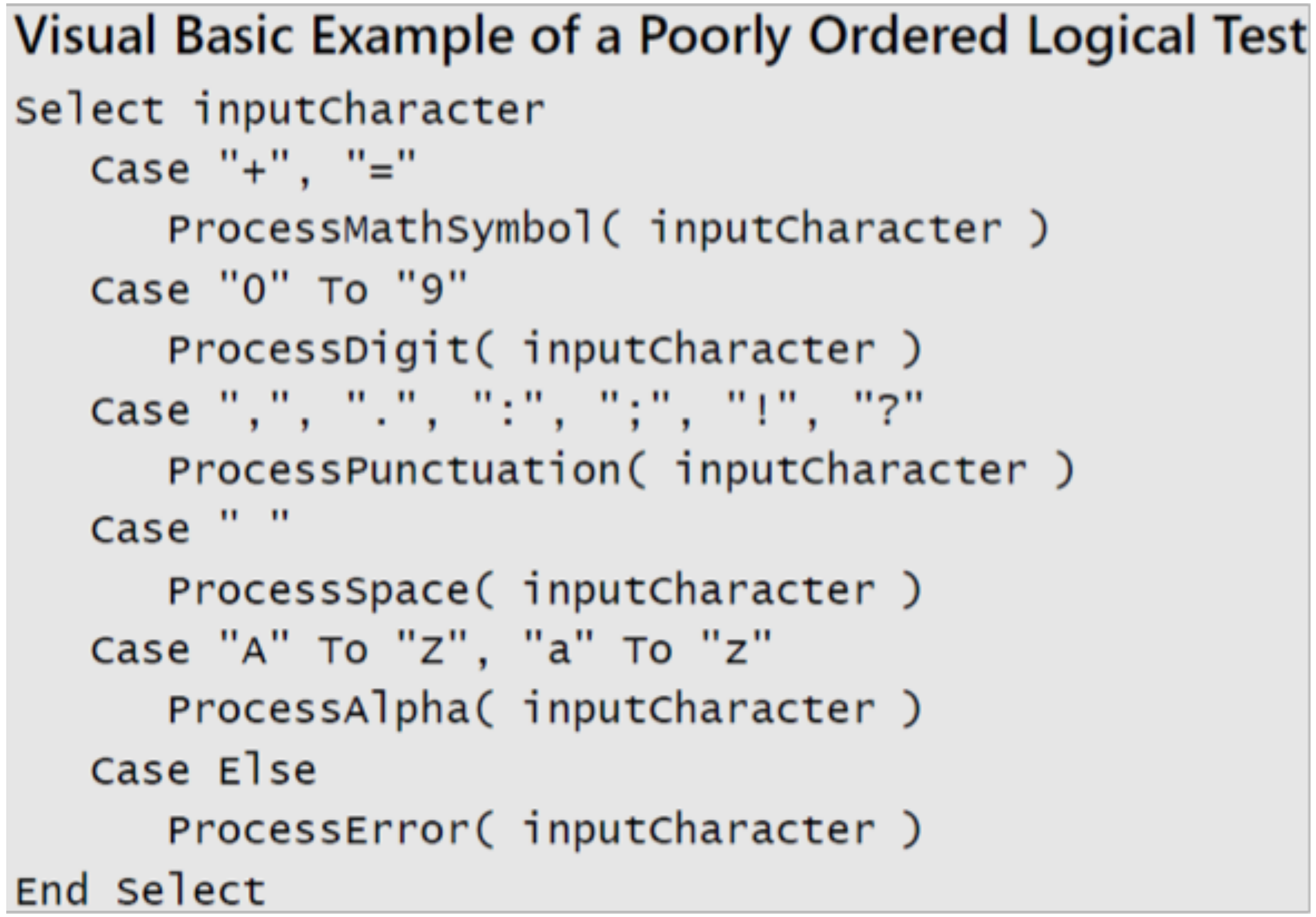
- Here’s a Visual Basic *Select-Case* statement that responds to keyboard input in a word processor
- **Any problem?**



```
Select inputCharacter
   Case "+", "="
      ProcessMathSymbol( inputCharacter )
   Case "0" To "9"
      ProcessDigit( inputCharacter )
   Case ",", ".", ":", ";", "!", "?"
      ProcessPunctuation( inputCharacter )
   Case " "
      ProcessSpace( inputCharacter )
   Case "A" To "Z", "a" To "z"
      ProcessAlpha( inputCharacter )
   Case Else
      ProcessError( inputCharacter )
End Select
```

Logic

- **Order Tests by Frequency**
- Here's a *Select-Case* statement that responds to keyboard input in a word processor:
- The cases in this *case* statement are ordered in something close to the ASCII sort order

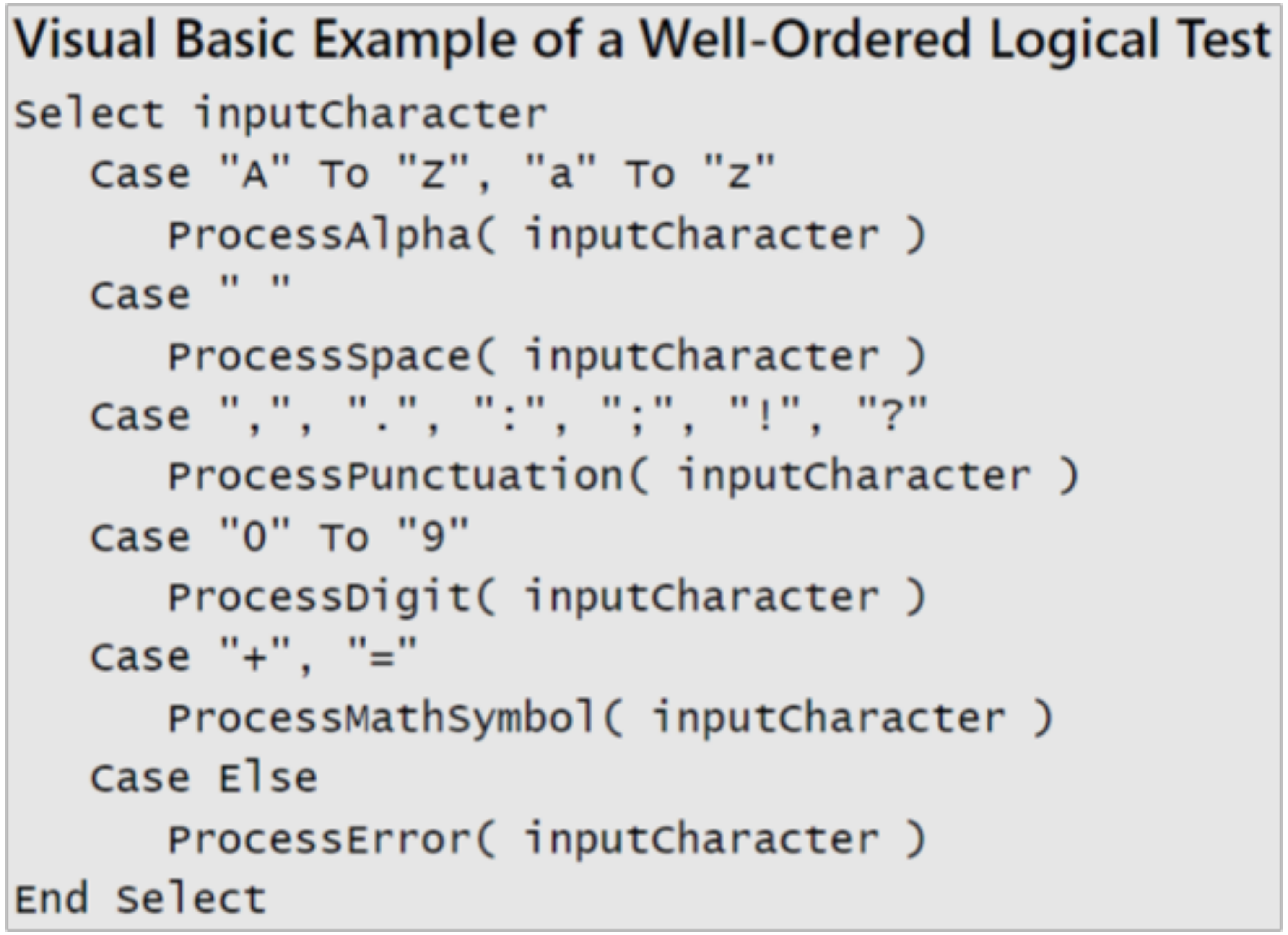


Visual Basic Example of a Poorly Ordered Logical Test

```
Select inputCharacter
   Case "+", "="
      ProcessMathSymbol( inputCharacter )
   Case "0" To "9"
      ProcessDigit( inputCharacter )
   Case ",", ".", ":", ";", "!", "?"
      ProcessPunctuation( inputCharacter )
   Case " "
      ProcessSpace( inputCharacter )
   Case "A" To "Z", "a" To "z"
      ProcessAlpha( inputCharacter )
   Case Else
      ProcessError( inputCharacter )
End Select
```

Logic

- **Order Tests by Frequency**
- Here's the reordered *case* statement:

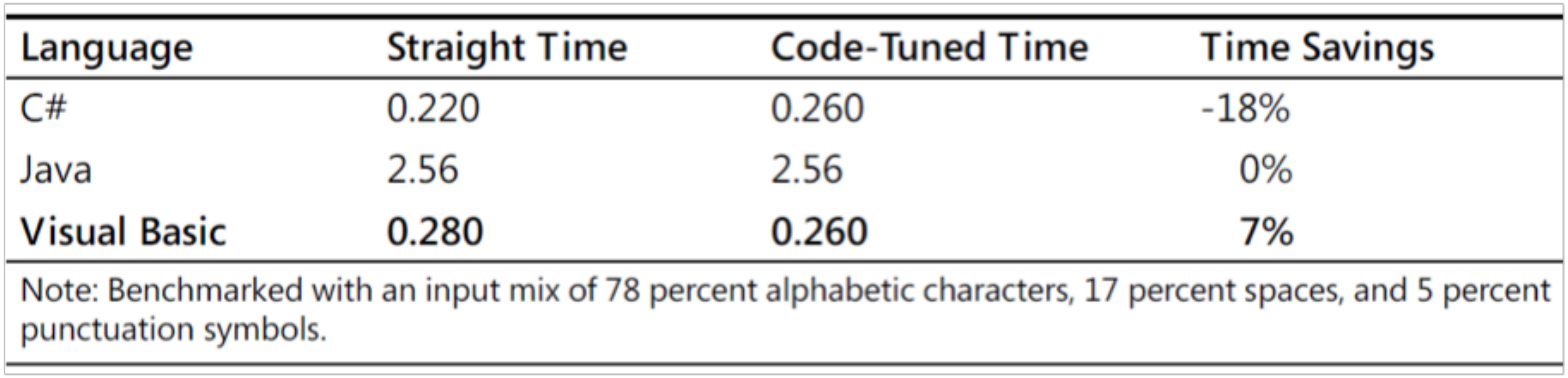


Visual Basic Example of a Well-Ordered Logical Test

```
Select inputCharacter
   Case "A" To "Z", "a" To "z"
      ProcessAlpha( inputCharacter )
   Case " "
      ProcessSpace( inputCharacter )
   Case ",", ".", ":", ";", "!", "?"
      ProcessPunctuation( inputCharacter )
   Case "0" To "9"
      ProcessDigit( inputCharacter )
   Case "+", "="
      ProcessMathSymbol( inputCharacter )
   Case Else
      ProcessError( inputCharacter )
End Select
```

Logic

- **Order Tests by Frequency**
- Because the most common case is usually found sooner in the optimized code, the net effect will be the performance of fewer tests. Following are the results of this optimization with a typical mix of characters:



Language	Straight Time	Code-Tuned Time	Time Savings
C#	0.220	0.260	-18%
Java	2.56	2.56	0%
Visual Basic	**0.280**	**0.260**	**7%**

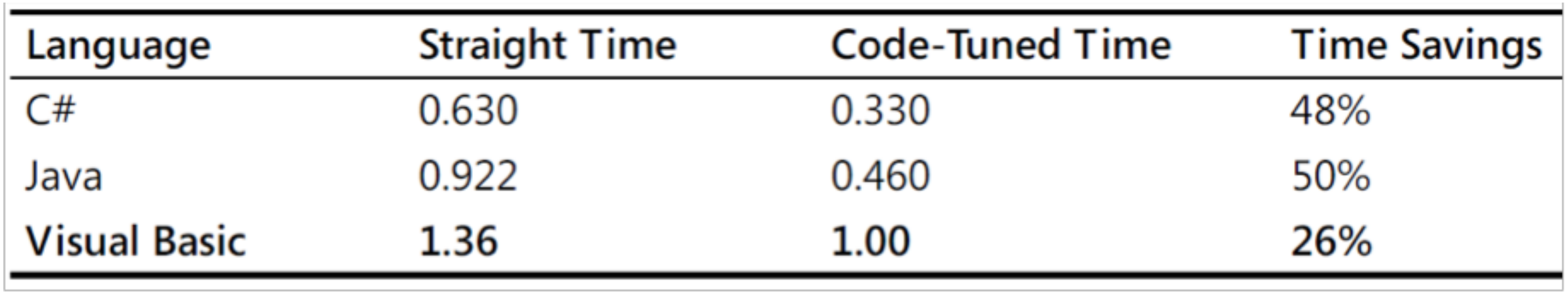
Note: Benchmarked with an input mix of 78 percent alphabetic characters, 17 percent spaces, and 5 percent punctuation symbols.

Logic

- **Order Tests by Frequency**
- The Microsoft Visual Basic results are as expected, but the Java and C# results are not as expected.
- Apparently that's because of the way *switch-case* statements are structured in C# and Java, the C# and Java code doesn't benefit from the optimization as the Visual Basic code does.
- This result underscores the importance of not following any optimization advice blindly—*specific compiler implementations will significantly affect the results*.

Logic

- **Order Tests by Frequency**
- You might assume that the code generated by the **Visual Basic** compiler for a set of ***if-then-elses*** that perform the same test as the *case* statement would be similar. Take a look at those results:



Language	Straight Time	Code-Tuned Time	Time Savings
C#	0.630	0.330	48%
Java	0.922	0.460	50%
Visual Basic	**1.36**	**1.00**	**26%**

Logic

- **Order Tests by Frequency**
- For the same number of tests, the **Visual Basic** compiler takes about five times as long in the unoptimized case, four times in the optimized case, compared to their **switch-case versions**.
- This suggests that the **compiler** is generating different code for the ***case*** approach than for the ***if-then-else*** approach.

Logic

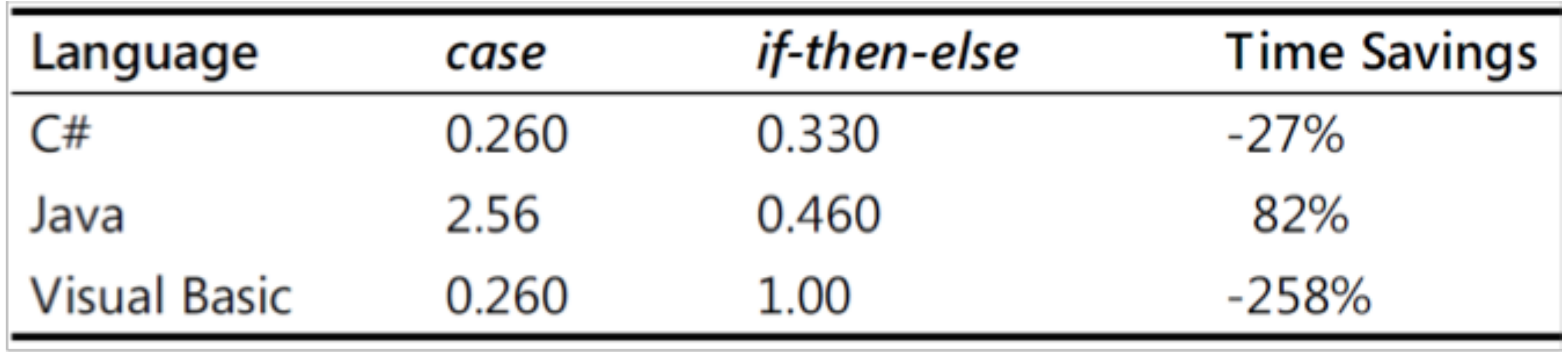
- **Order Tests by Frequency**
- The improvement with *if-then-else*s is more consistent than it was with the *case* statements, but that's a mixed blessing.
- In C# and Visual Basic, both versions of the *case* statement approach are faster than both versions of the *if-then-else* approach, whereas in Java both versions are slower.
- This variation in results suggests a third possible optimization, we will see later.

Logic

- **Compare Performance of Similar Logic Structures**
- The test described above could be performed using either a *case* statement or *if-thenelse*s.
- Depending on the environment, either approach might work better.
- Here is the data from the preceding two tables reformatted to present the "**code-tuned**" times comparing ***if-then-else*** and ***case*** performance:

Logic

- In **Visual Basic**, *case* is dramatically superior to *if-then-else*, and in another, *if-then-else* is dramatically superior to *case*.
- In **C#**, the difference is relatively small. You might think that because C# and Java share similar syntax for *case* statements, their results would be similar, but in fact their results are opposite each other.
- This example clearly illustrates the difficulty of performing any sort of "**rule of thumb**" or "**logic**" to code tuning—there is simply no reliable substitute for *measuring* results.



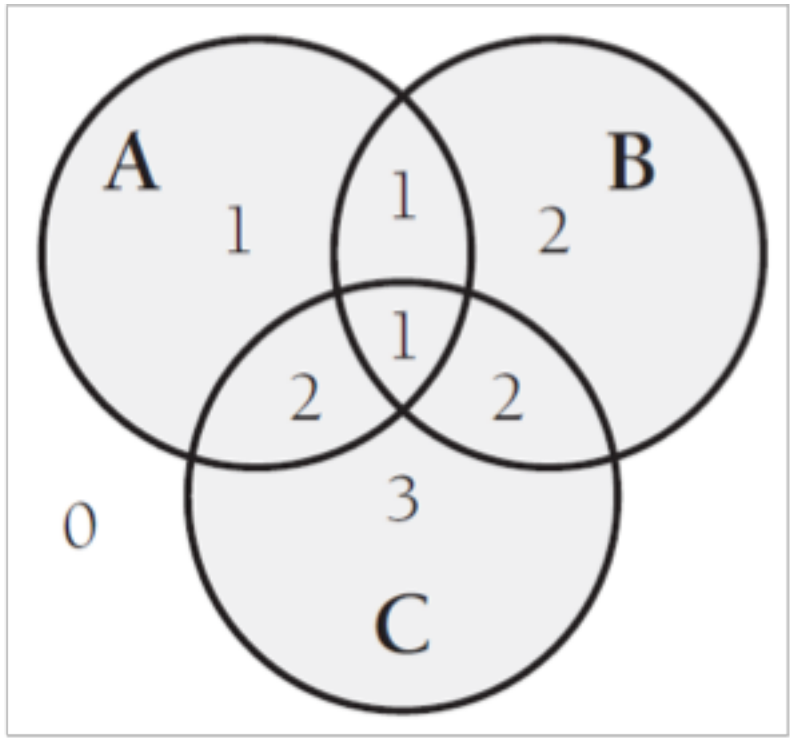
Language	*case*	*if-then-else*	Time Savings
C#	0.260	0.330	-27%
Java	2.56	0.460	82%
Visual Basic	0.260	1.00	-258%

Logic

- **Substitute Table Lookups for Complicated Expressions**
- In some circumstances, a table lookup might be quicker than traversing a complicated chain of logic.
- The point of a complicated chain is usually to categorize something and then to take an action based on its category.

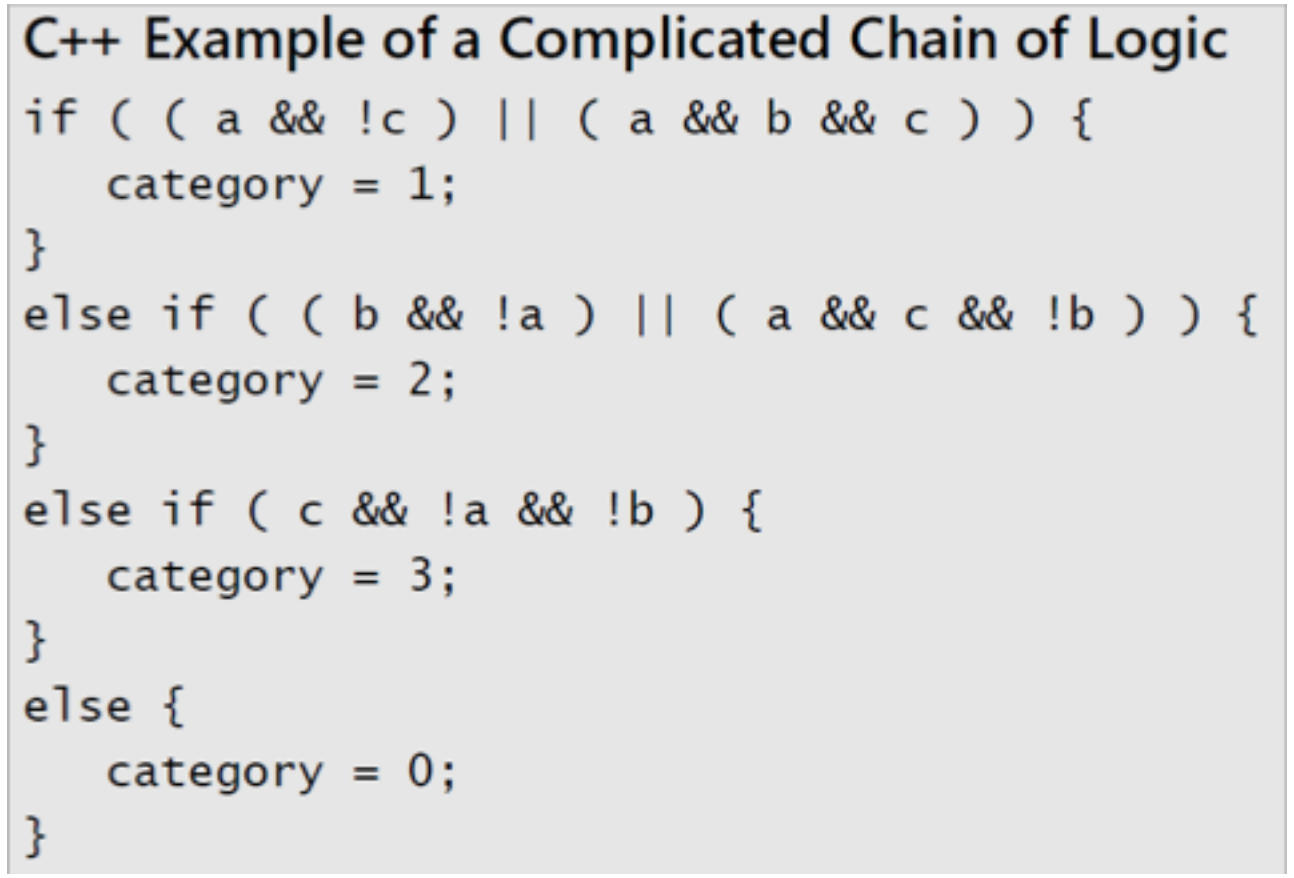
Logic

- **Substitute Table Lookups for Complicated Expressions**
- As an abstract example, suppose you want to assign a category number to something based on which of three groups—Groups *A*, *B*, and *C*—it falls into:

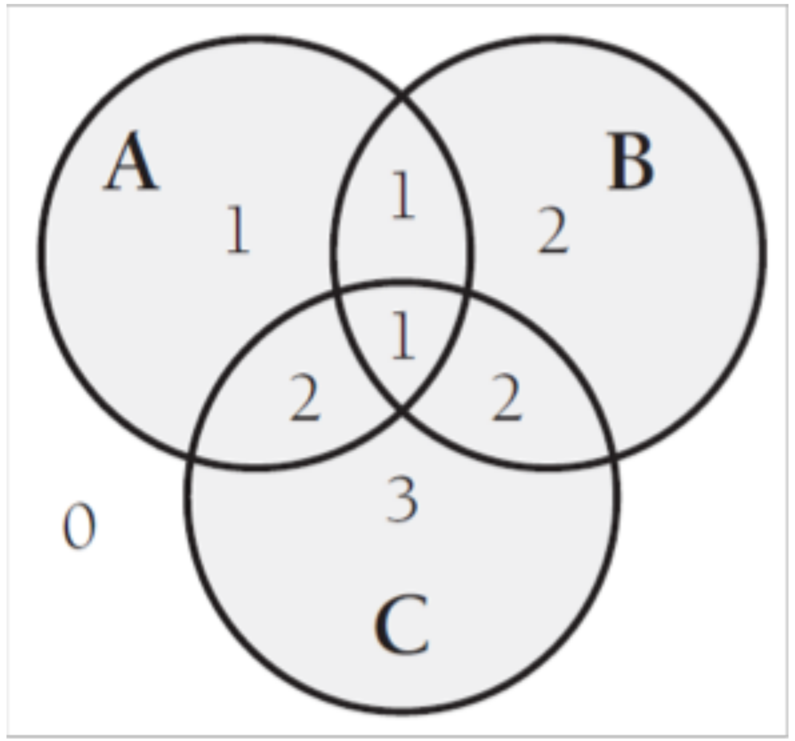


Logic

- **Substitute Table Lookups for Complicated Expressions**
- This complicated logic chain assigns the category numbers:

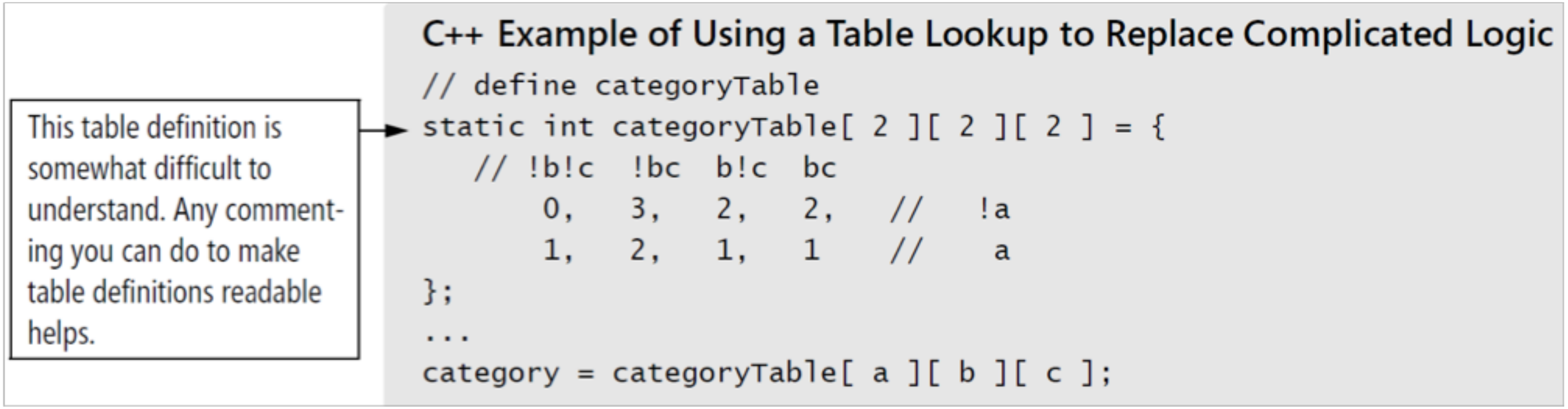

C++ Example of a Complicated Chain of Logic

```cpp
if ( ( a && !c ) || ( a && b && c ) ) {
   category = 1;
}
else if ( ( b && !a ) || ( a && c && !b ) ) {
   category = 2;
}
else if ( c && !a && !b ) {
   category = 3;
}
else {
   category = 0;
}
```



Logic

- **Substitute Table Lookups for Complicated Expressions**
- You can replace this test with a more modifiable and higher-performance lookup table:



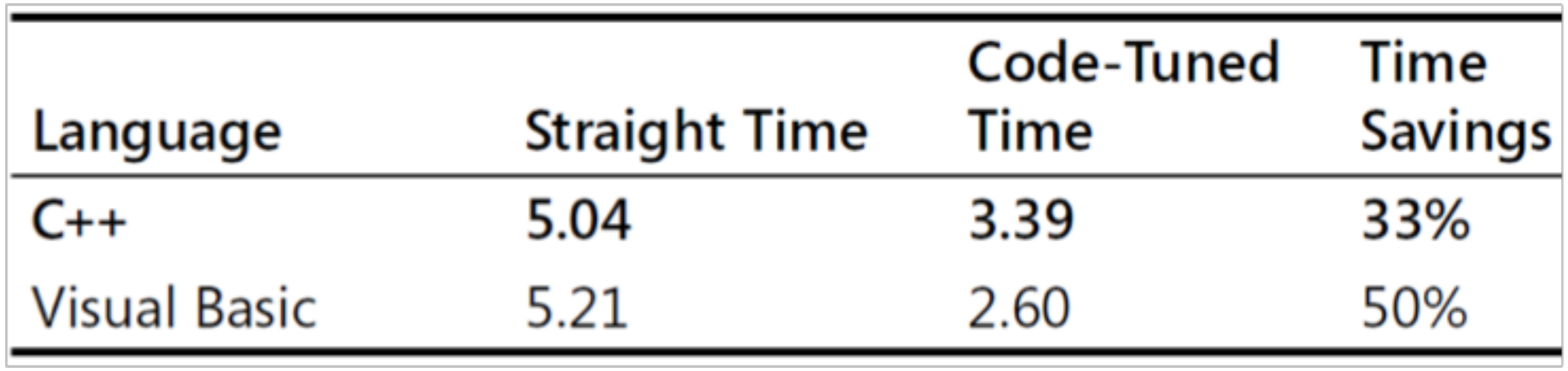
This table definition is somewhat difficult to understand. Any commenting you can do to make table definitions readable helps.

C++ Example of Using a Table Lookup to Replace Complicated Logic

```
// define categoryTable
static int categoryTable[ 2 ][ 2 ][ 2 ] = {
   // !b!c  !bc  b!c  bc
        0,   3,   2,   2,   //   !a
        1,   2,   1,   1    //    a
};
...
category = categoryTable[ a ][ b ][ c ];
```

Logic

- **Substitute Table Lookups for Complicated Expressions**
- Although the definition of the table is hard to read, if it's well documented it won't be any harder to read than the code for the complicated chain of logic was. If the definition changes, the table will be much easier to maintain than the earlier logic would have been. Here are the performance results:



Language	Straight Time	Code-Tuned Time	Time Savings
C++	5.04	3.39	33%
Visual Basic	5.21	2.60	50%

Logic

- **Use Lazy Evaluation**
- If a program uses lazy evaluation, it avoids doing any work until the work is needed.
- For example, a program contains a table of 5000 values, generates the whole table at startup time, and then uses it as the program executes.
- If the program uses only a small percentage of the entries in the table, it might make more sense to compute them as they're needed rather than all at once.
- Once an entry is computed, it can still be stored for future reference (otherwise known as "cached").

Outline

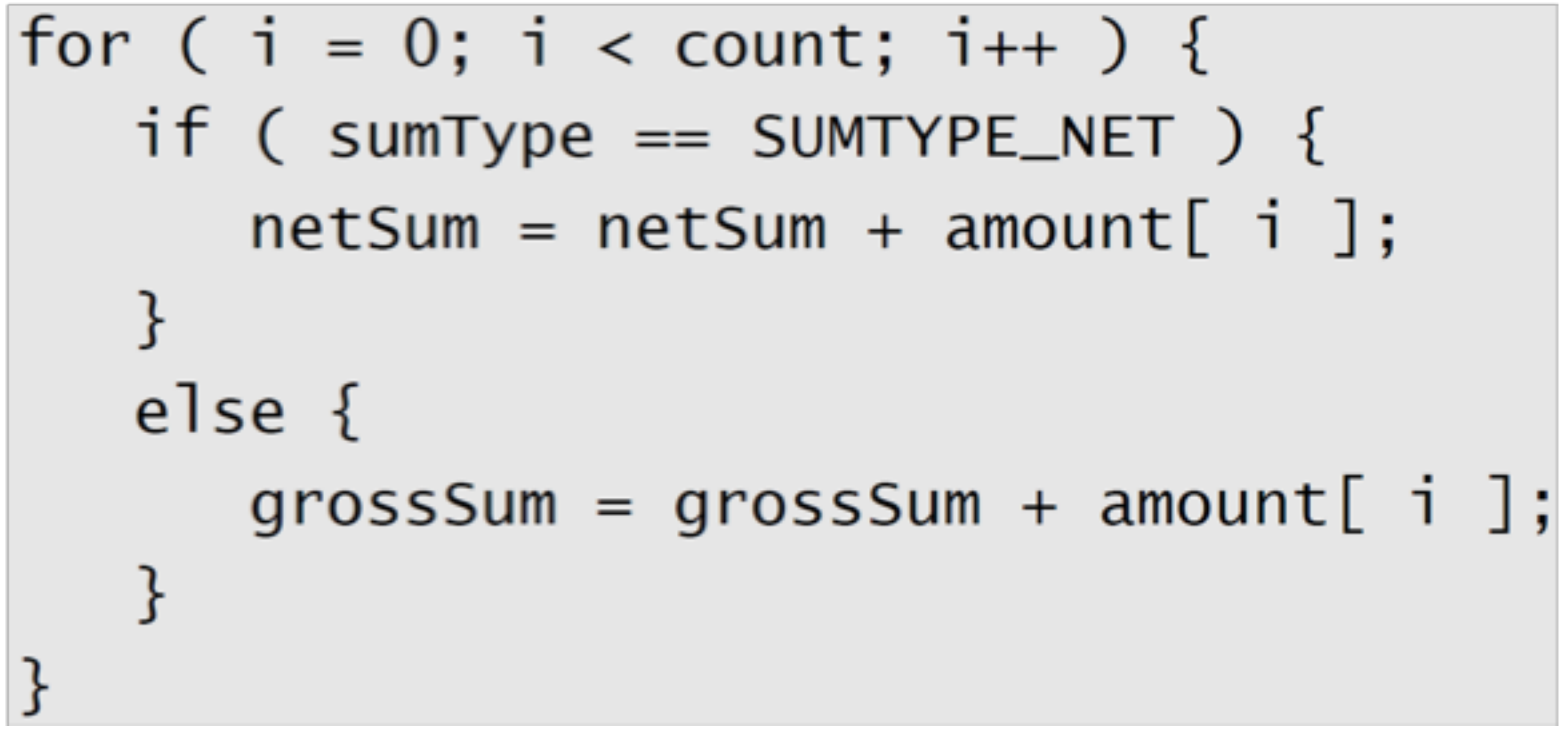
- Logic
- Loops
- Data Transformations
- Expressions

Loops

- Because loops are executed many times, the hot spots in a program are often inside loops.
- The techniques in this section make the loop itself faster.

Loops

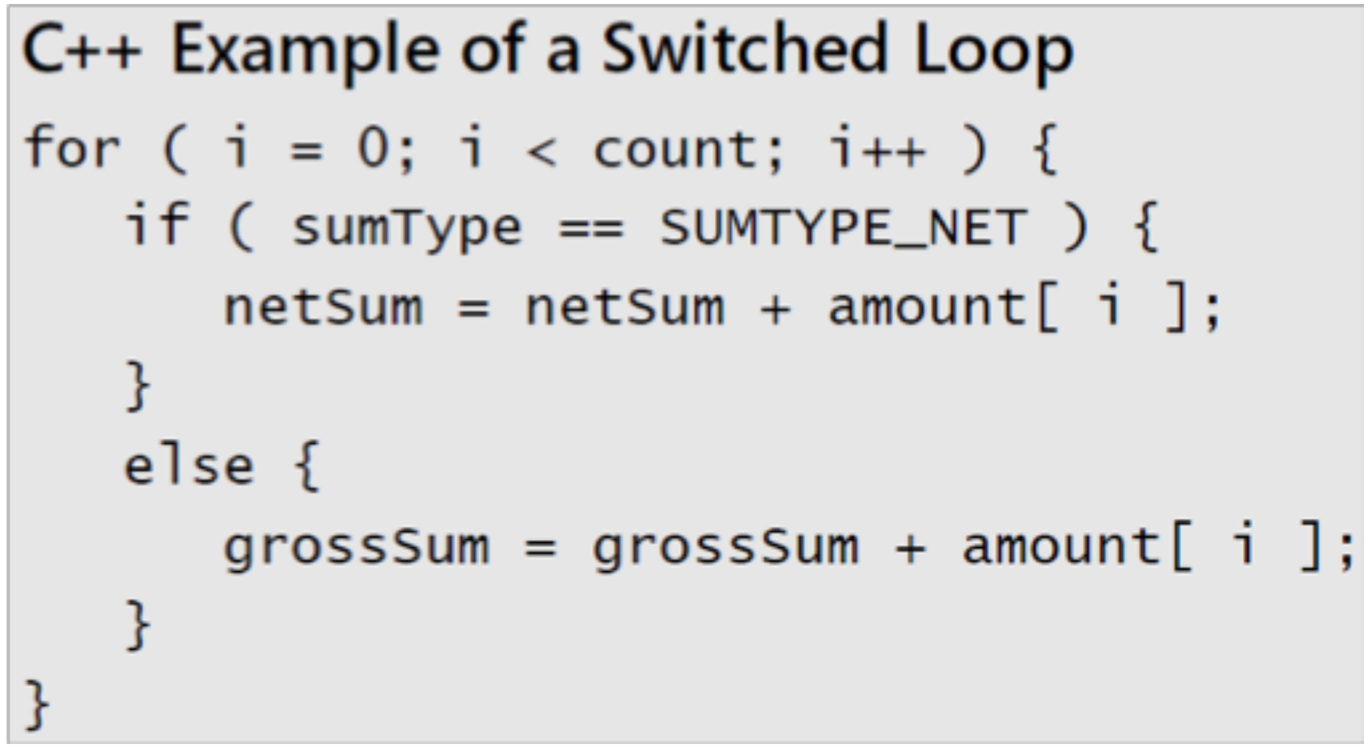
- **Any possible issues in terms of performance?**



```
for ( i = 0; i < count; i++ ) {
    if ( sumType == SUMTYPE_NET ) {
        netSum = netSum + amount[ i ];
    }
    else {
        grossSum = grossSum + amount[ i ];
    }
}
```

Loops – Unswitching

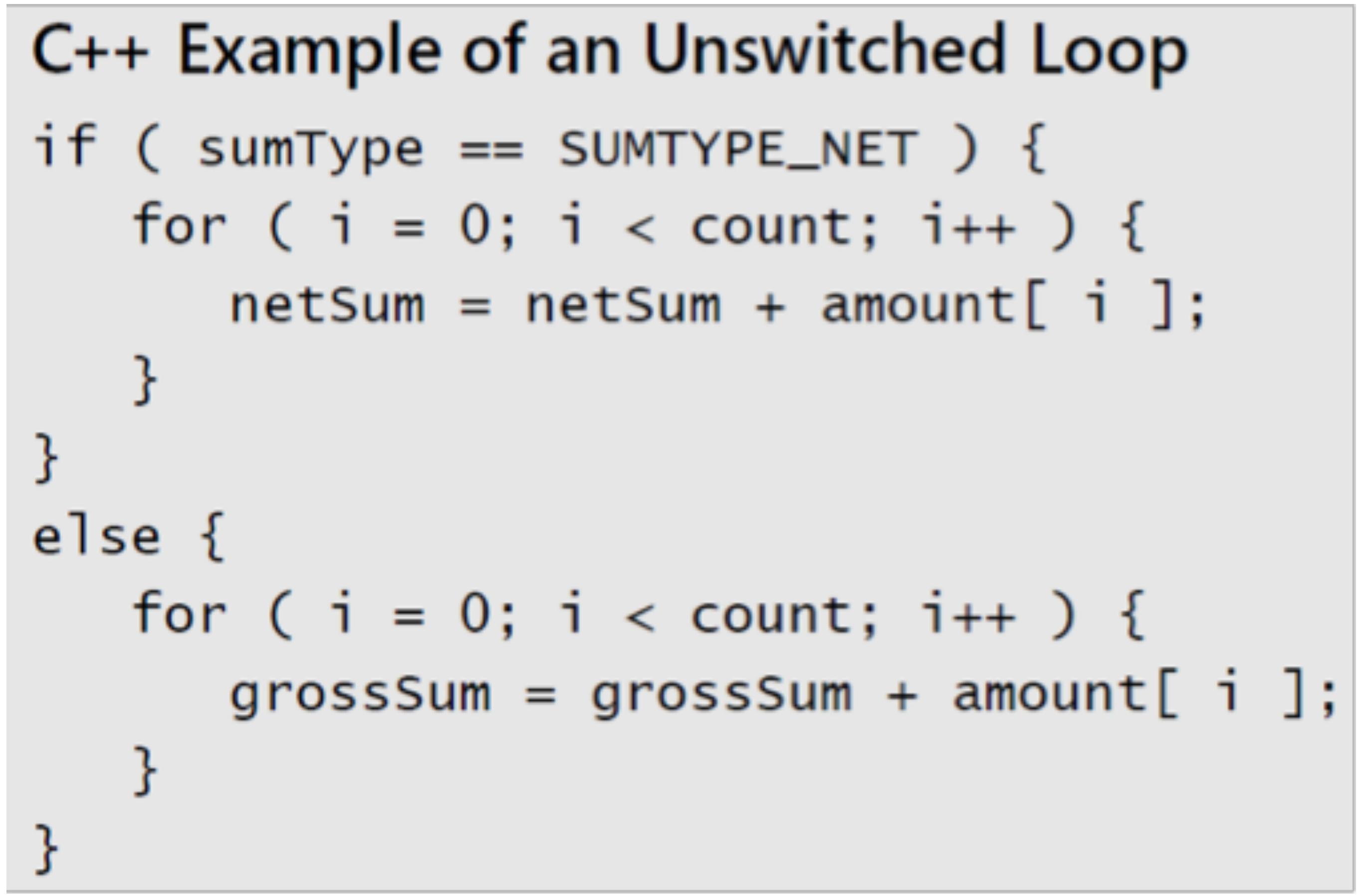
- Switching *refers to making a decision inside a loop every time it's executed*. If the decision doesn't change while the loop is executing, you can unswitch the loop by making the decision outside the loop.
- Usually this requires turning the loop inside out, putting loops inside the conditional rather than putting the conditional inside the loop.
- An example of a loop before unswitching:


C++ Example of a Switched Loop

```
for ( i = 0; i < count; i++ ) {
   if ( sumType == SUMTYPE_NET ) {
      netSum = netSum + amount[ i ];
   }
   else {
      grossSum = grossSum + amount[ i ];
   }
}
```

Loops – Unswitching

- In this code, the test *if (sumType == SUMTYPE_NET)* is repeated through each iteration, even though it'll be the same each time through the loop.
- You can rewrite the code for a speed gain this way:

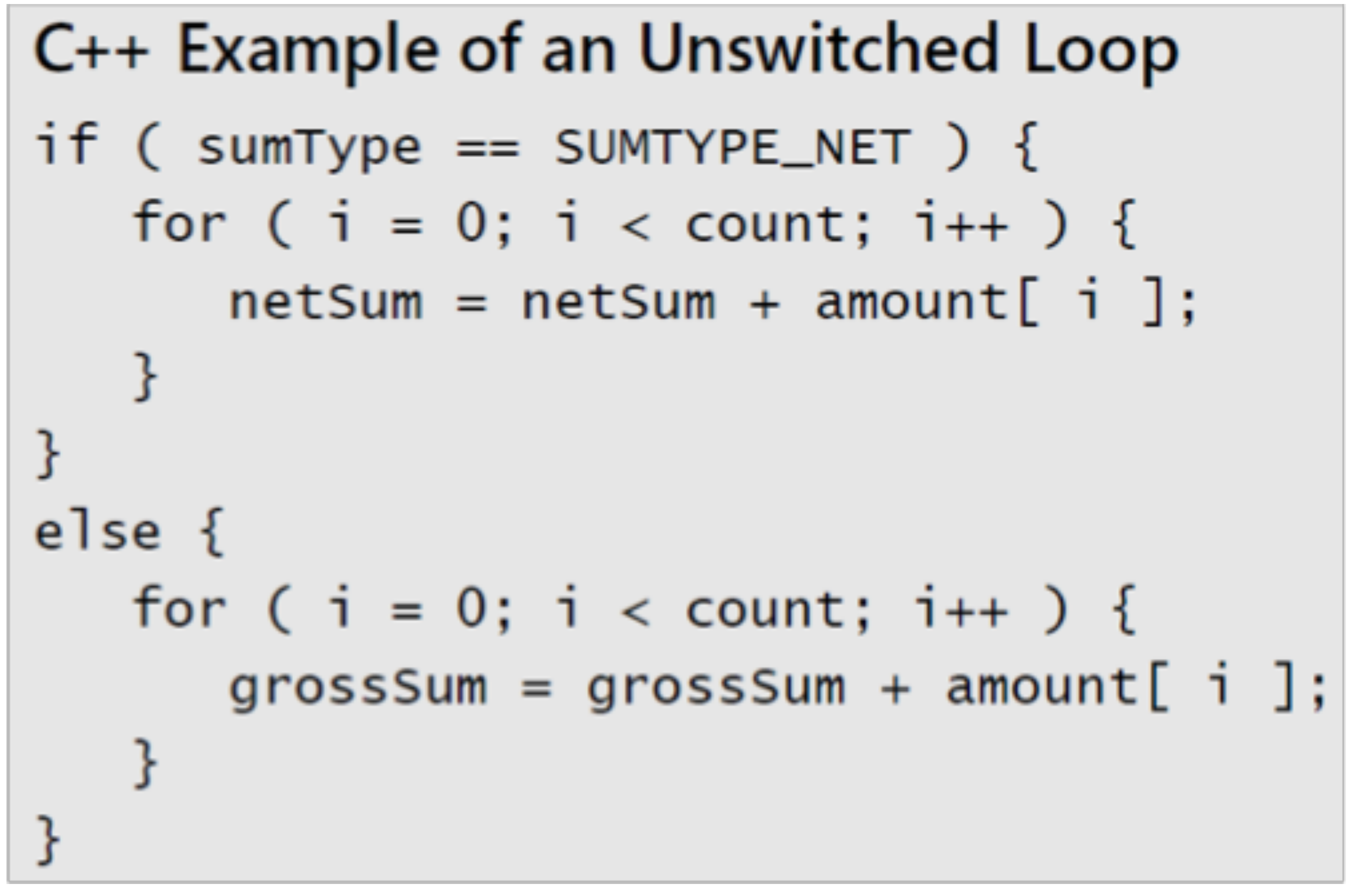


C++ Example of an Unswitched Loop

```
if ( sumType == SUMTYPE_NET ) {
   for ( i = 0; i < count; i++ ) {
      netSum = netSum + amount[ i ];
   }
}
else {
   for ( i = 0; i < count; i++ ) {
      grossSum = grossSum + amount[ i ];
   }
}
```

Loops – Unswitching

- Good code?
- This code fragment violates several rules of good programming.
- Readability and maintenance are usually more important than execution speed or size, but the current topic is performance, and that implies a tradeoff with the other objectives

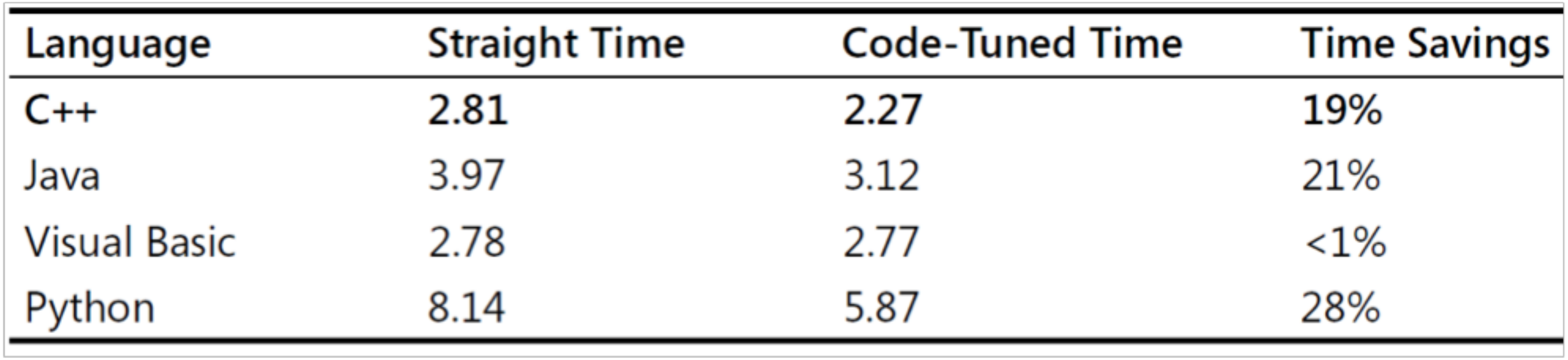


C++ Example of an Unswitched Loop

```
if ( sumType == SUMTYPE_NET ) {
   for ( i = 0; i < count; i++ ) {
      netSum = netSum + amount[ i ];
   }
}
else {
   for ( i = 0; i < count; i++ ) {
      grossSum = grossSum + amount[ i ];
   }
}
```

Loops – Unswitching

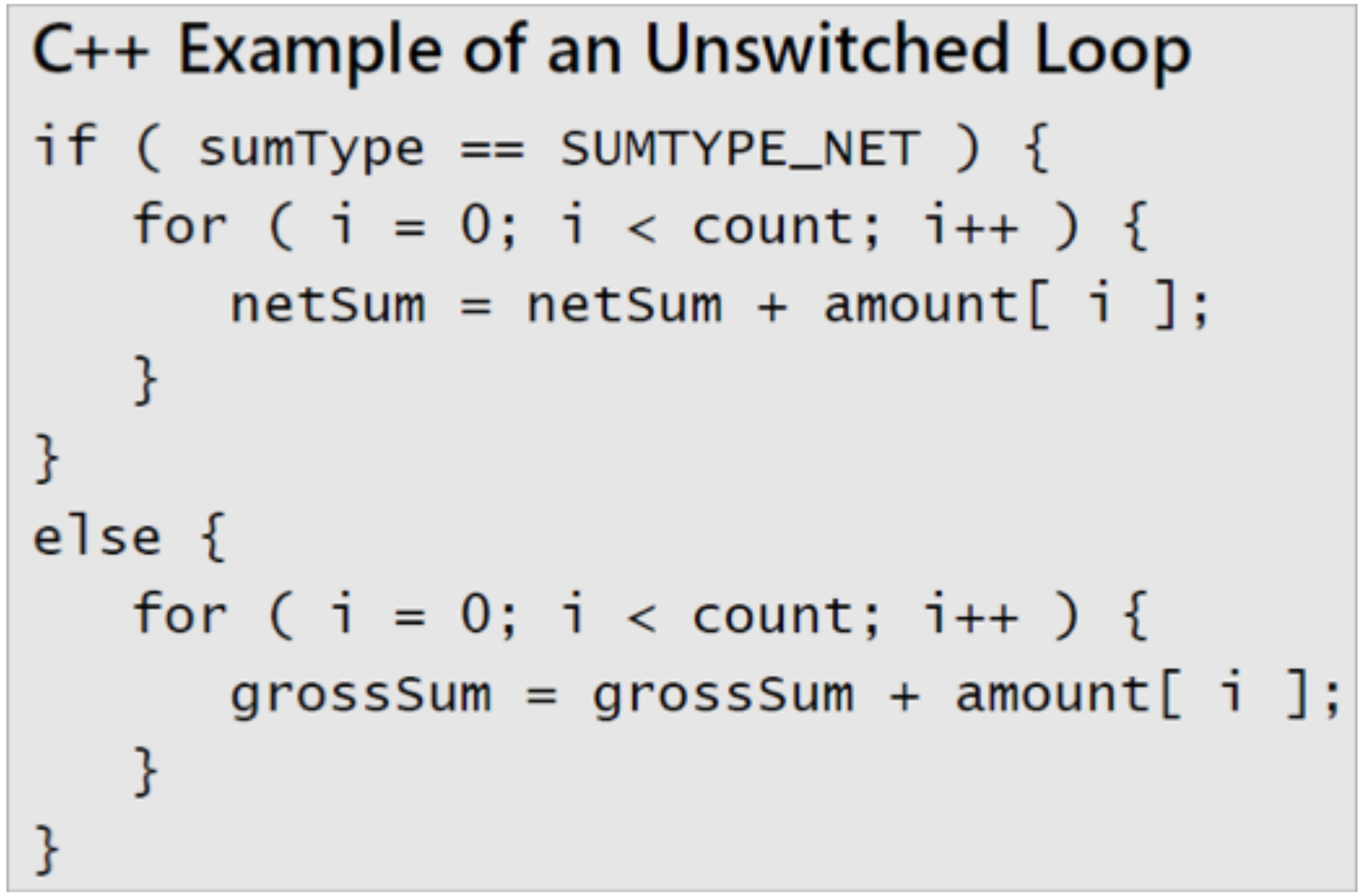
- This is good for about a 20 percent time savings:



Language	Straight Time	Code-Tuned Time	Time Savings
C++	**2.81**	**2.27**	**19%**
Java	3.97	3.12	21%
Visual Basic	2.78	2.77	<1%
Python	8.14	5.87	28%

Loops – Unswitching

- Also, **the case is that the two loops have to be maintained in parallel**.
- If *count* changes to *clientCount*, you have to remember to change it in both places, which is an annoyance for you and a maintenance headache for anyone else who has to work with the code.

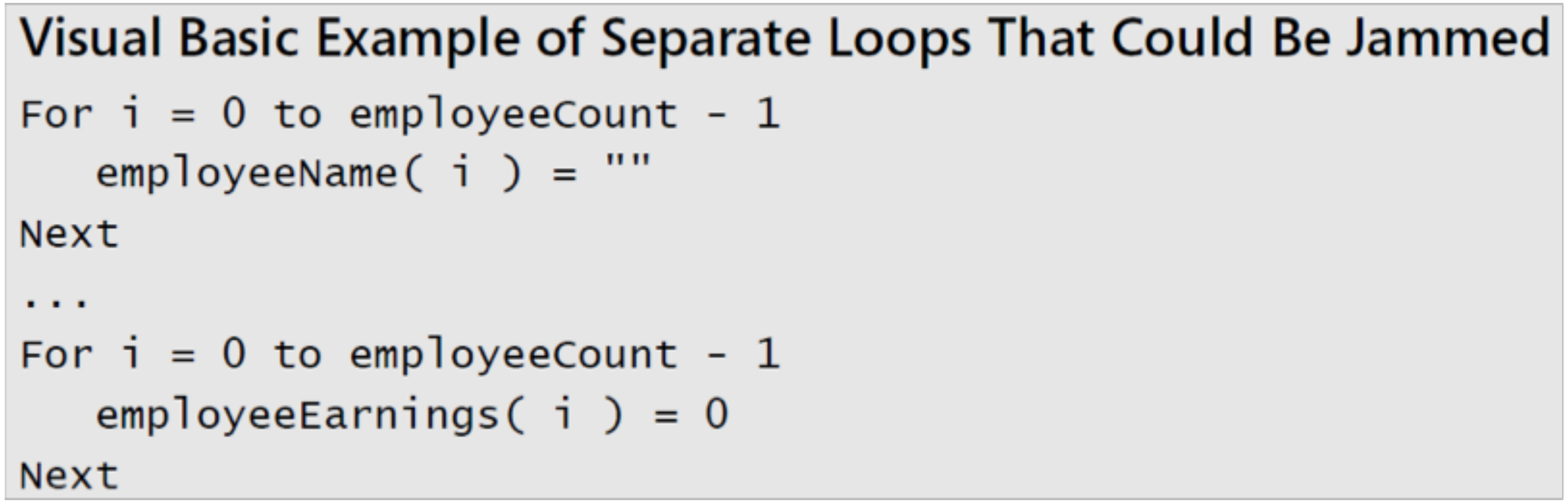


C++ Example of an Unswitched Loop

```
if ( sumType == SUMTYPE_NET ) {
   for ( i = 0; i < count; i++ ) {
      netSum = netSum + amount[ i ];
   }
}
else {
   for ( i = 0; i < count; i++ ) {
      grossSum = grossSum + amount[ i ];
   }
}
```

Loops – Jamming

- **Jamming**, or "**fusion**," is the result of **combining two loops** that operate on the same set of elements. The gain lies in cutting the loop overhead from two loops to one.
- Here's a candidate for loop jamming:

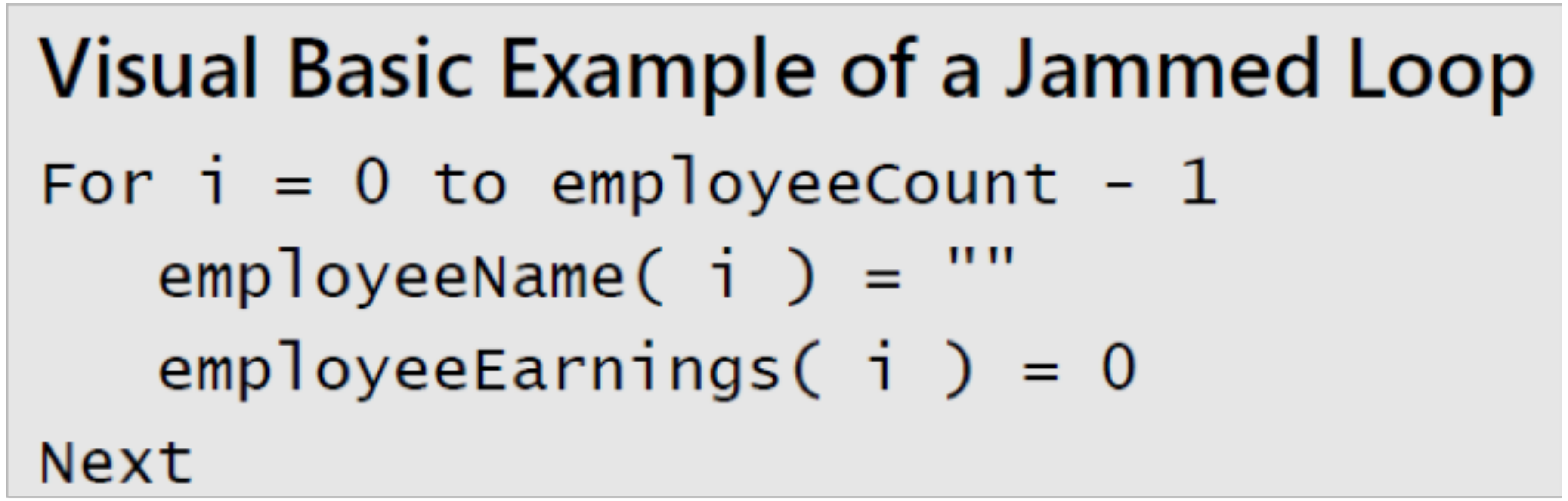


Visual Basic Example of Separate Loops That Could Be Jammed

```
For i = 0 to employeeCount - 1
   employeeName( i ) = ""
Next
...
For i = 0 to employeeCount - 1
   employeeEarnings( i ) = 0
Next
```

Loops – Jamming

- When you jam loops, you find code in two loops that you can combine into one.
- Usually, that means the loop counters have to be the same. In this example, both loops run **from *0* to *employeeCount - 1***, so you can **jam** them:

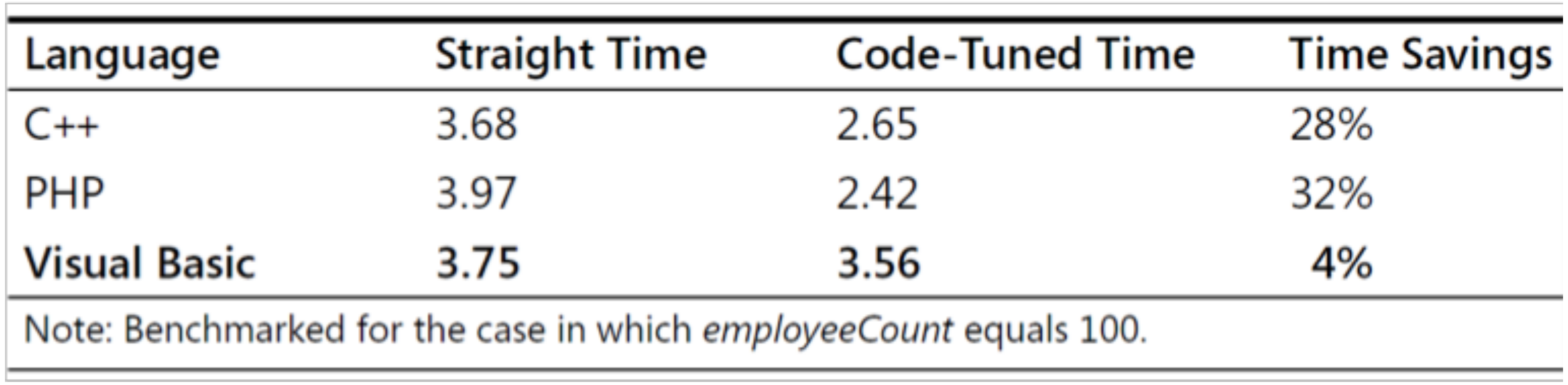


Visual Basic Example of a Jammed Loop

```
For i = 0 to employeeCount - 1
   employeeName( i ) = ""
   employeeEarnings( i ) = 0
Next
```

Loops – Jamming

- Here are the savings:



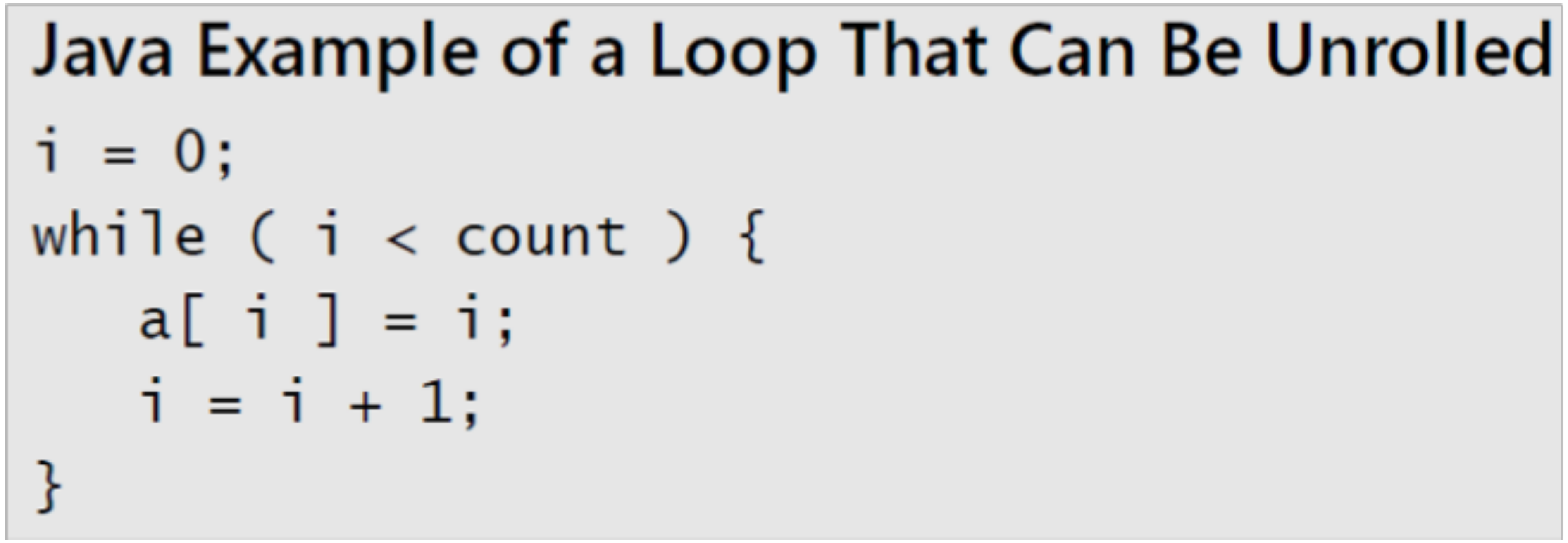
Language	Straight Time	Code-Tuned Time	Time Savings
C++	3.68	2.65	28%
PHP	3.97	2.42	32%
Visual Basic	**3.75**	**3.56**	**4%**

Note: Benchmarked for the case in which *employeeCount* equals 100.

- As before, the results vary significantly among languages.

Loops – Unrolling

- The goal of loop unrolling is to reduce the amount of loop iterations.
- Although completely unrolling a loop is a fast solution and works well when you're dealing with a small number of elements, it's not practical when you have a large number of elements or when you don't know in advance how many elements you'll have.

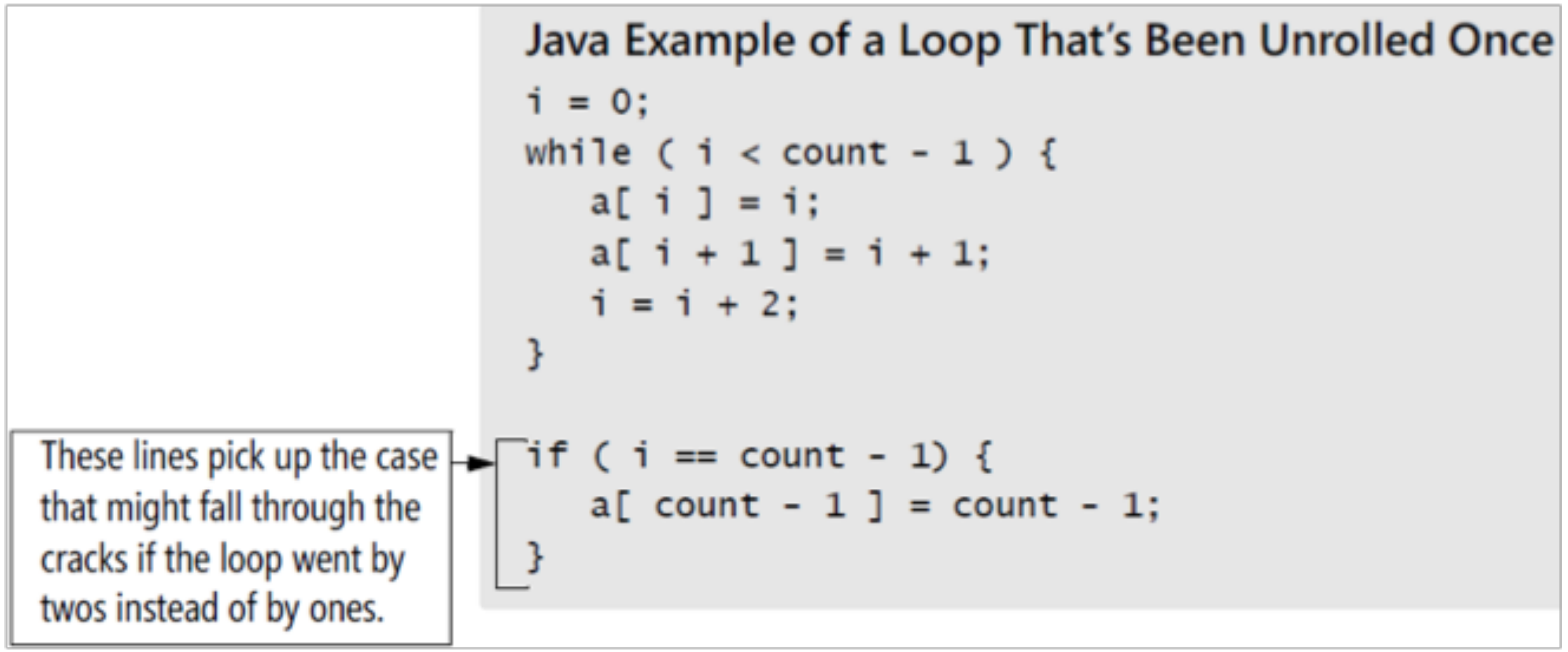


Java Example of a Loop That Can Be Unrolled

```
i = 0;
while ( i < count ) {
    a[ i ] = i;
    i = i + 1;
}
```

Loops – Unrolling

- To unroll the loop partially, you handle two or more cases in each pass through the loop instead of one.
- This unrolling hurts readability but doesn't hurt the generality of the loop. Here's the loop unrolled once:



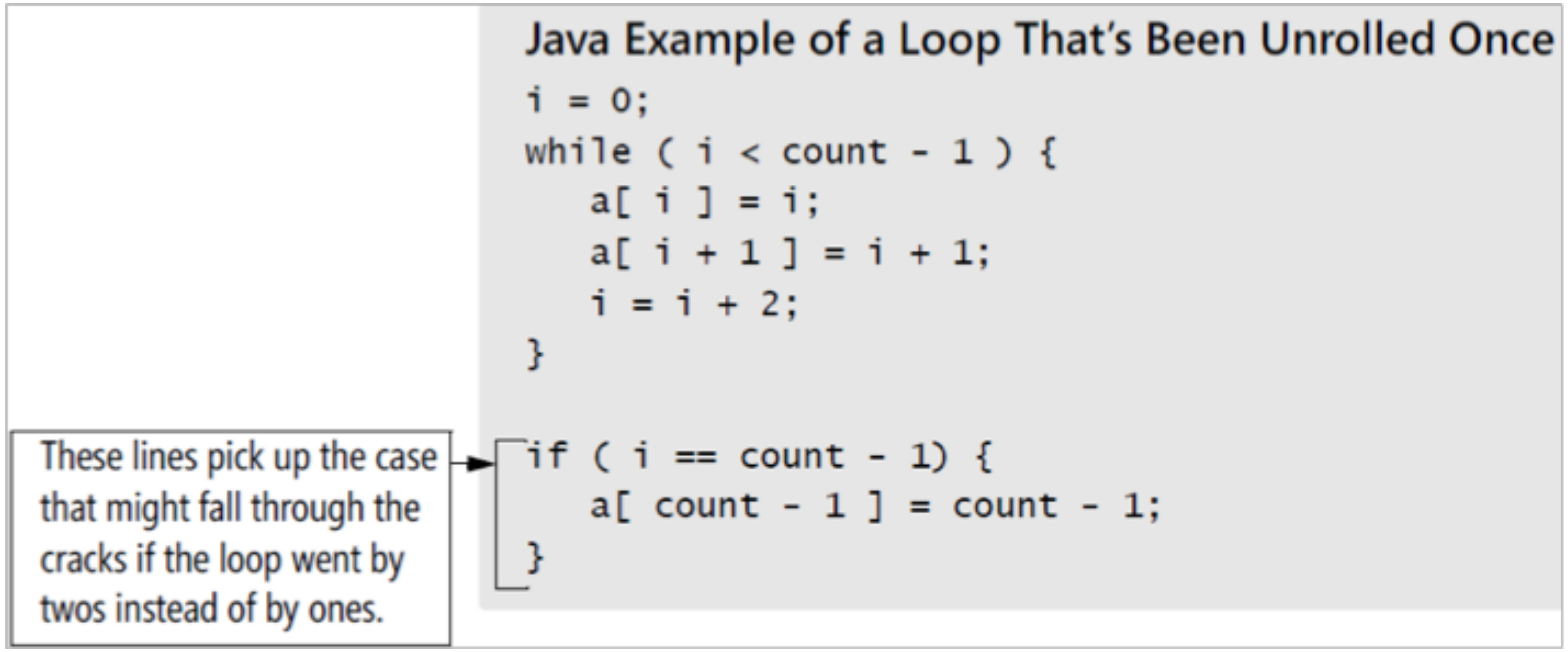
Java Example of a Loop That's Been Unrolled Once

```
i = 0;
while ( i < count - 1 ) {
   a[ i ] = i;
   a[ i + 1 ] = i + 1;
   i = i + 2;
}

if ( i == count - 1) {
   a[ count - 1 ] = count - 1;
}
```

These lines pick up the case that might fall through the cracks if the loop went by twos instead of by ones.

Loops – Unrolling

- The technique **replaced the original *a[i] = i* line with two lines, and *i* is incremented by *2* rather than by *1***. The extra code after the *while* loop is needed when *count* is odd and the loop has one iteration left after the loop terminates.



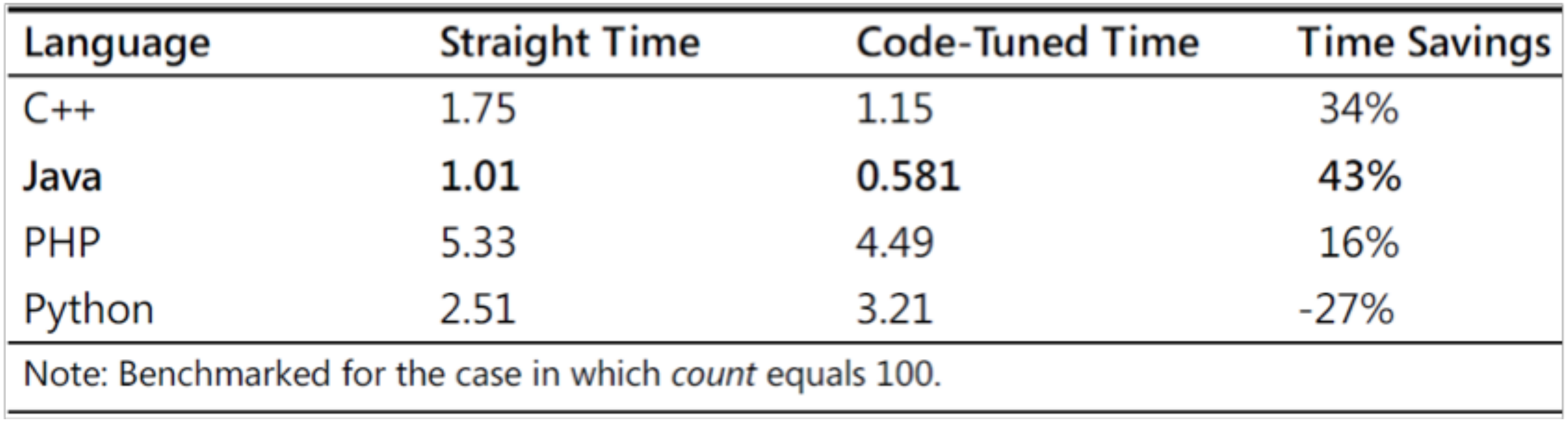
Java Example of a Loop That's Been Unrolled Once

```
i = 0;
while ( i < count - 1 ) {
   a[ i ] = i;
   a[ i + 1 ] = i + 1;
   i = i + 2;
}

if ( i == count - 1) {
   a[ count - 1 ] = count - 1;
}
```

These lines pick up the case that might fall through the cracks if the loop went by twos instead of by ones.

Loops – Unrolling

- A gain of 16 to 43 percent is respectable, although Python benchmark shows performance loss.
- The main hazard of loop unrolling is an off-by-one error in the code after the loop that picks up the last case.

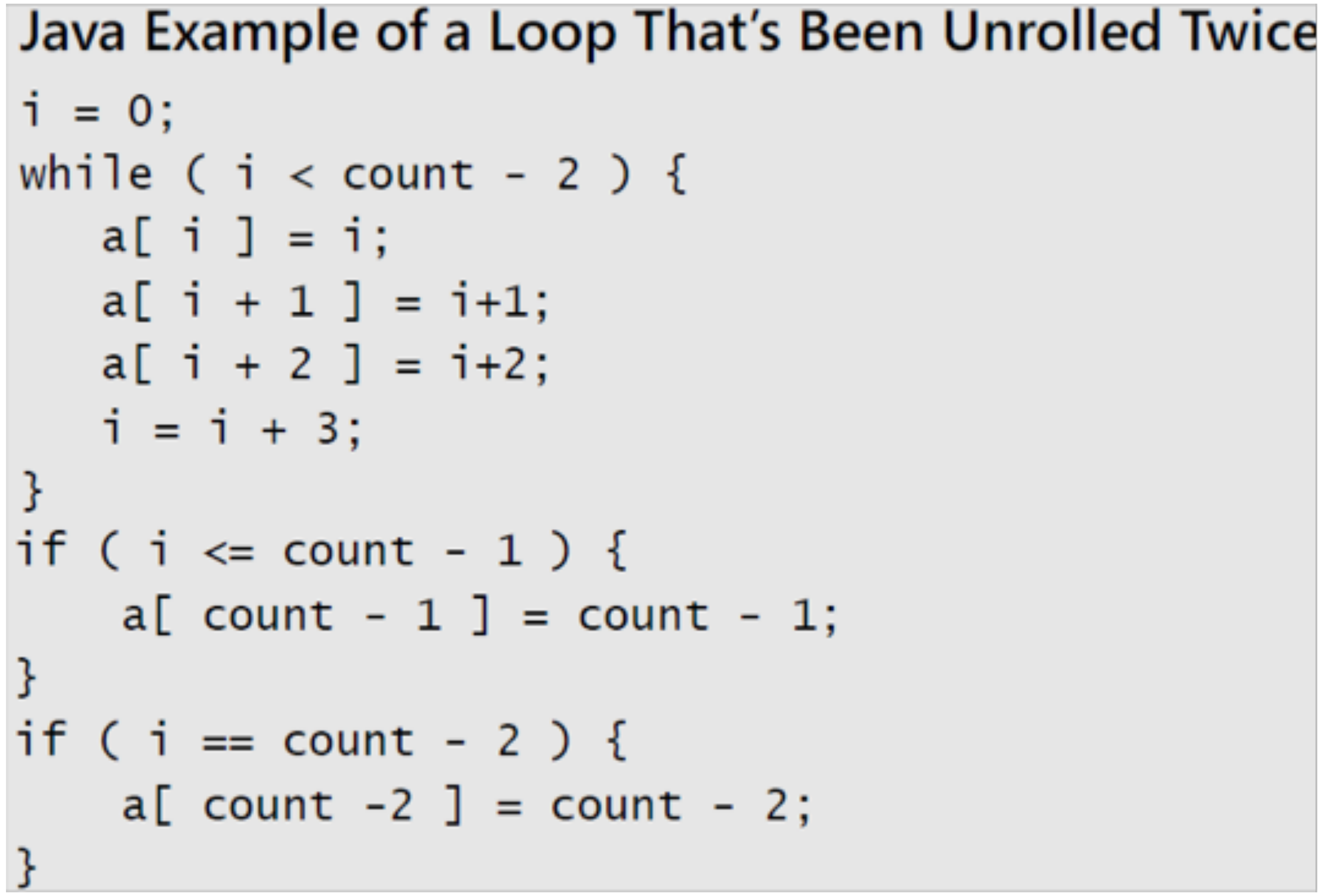


Language	Straight Time	Code-Tuned Time	Time Savings
C++	1.75	1.15	34%
Java	**1.01**	**0.581**	**43%**
PHP	5.33	4.49	16%
Python	2.51	3.21	-27%

Note: Benchmarked for the case in which *count* equals 100.

Loops – Unrolling

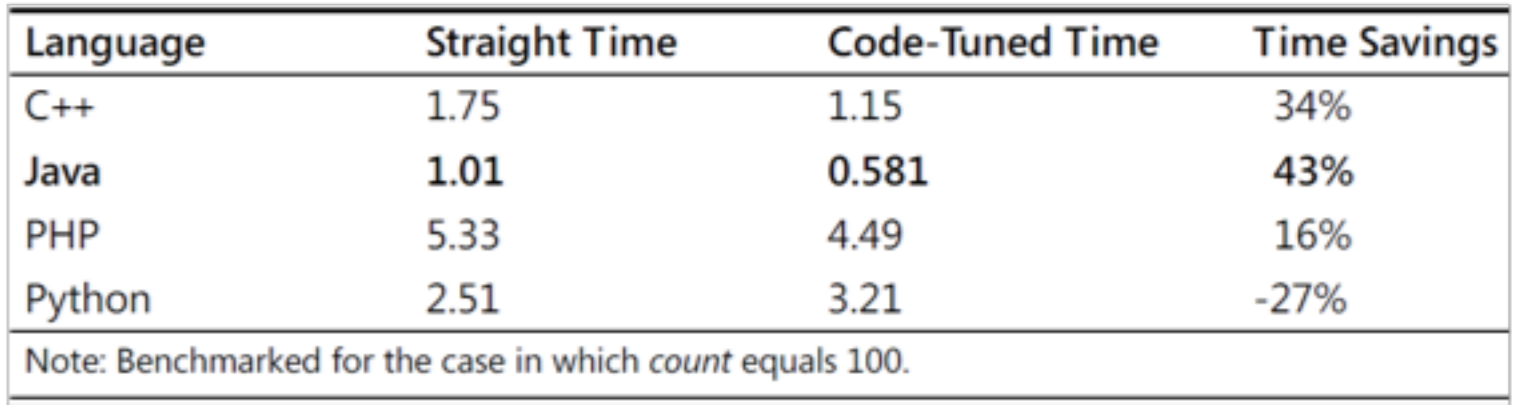
- What if you unroll the loop even further, going for two or more unrollings? Do you get more benefit if you unroll a loop twice?



Java Example of a Loop That's Been Unrolled Twice

```
i = 0;
while ( i < count - 2 ) {
   a[ i ] = i;
   a[ i + 1 ] = i+1;
   a[ i + 2 ] = i+2;
   i = i + 3;
}
if ( i <= count - 1 ) {
    a[ count - 1 ] = count - 1;
}
if ( i == count - 2 ) {
    a[ count -2 ] = count - 2;
}
```

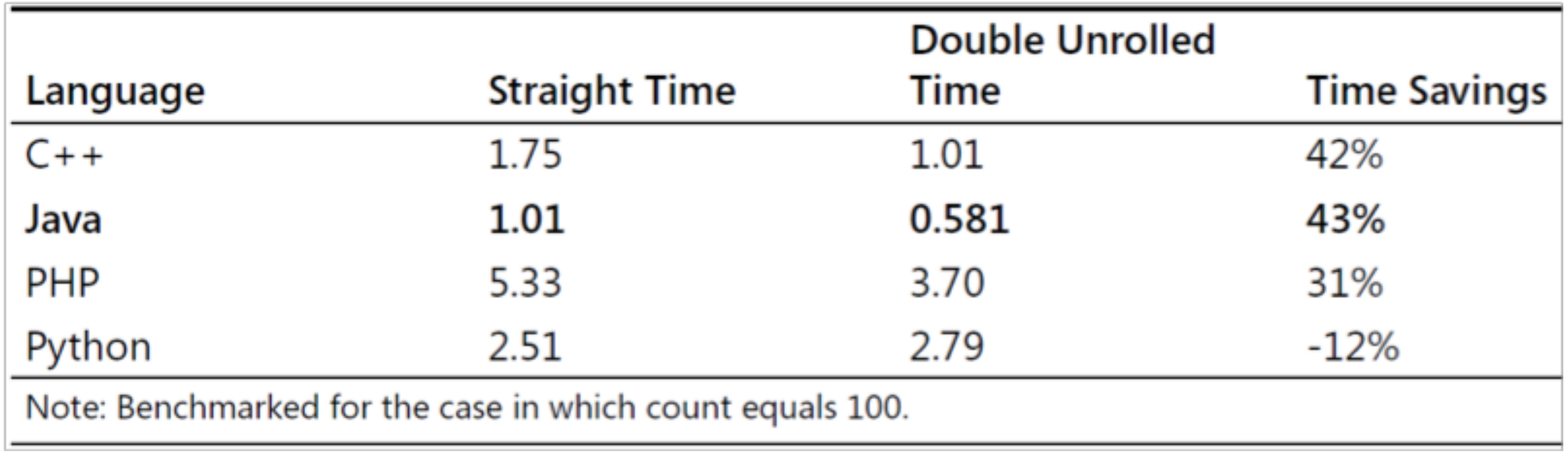
Loops – Unrolling



Language	Straight Time	Code-Tuned Time	Time Savings
C++	1.75	1.15	34%
Java	**1.01**	**0.581**	**43%**
PHP	5.33	4.49	16%
Python	2.51	3.21	-27%

Note: Benchmarked for the case in which *count* equals 100.

- Here are the results of unrolling the loop the second time (above single unrolling):



Language	Straight Time	Double Unrolled Time	Time Savings
C++	1.75	1.01	42%
Java	**1.01**	**0.581**	**43%**
PHP	5.33	3.70	31%
Python	2.51	2.79	-12%

Note: Benchmarked for the case in which count equals 100.

- The results indicate that **further loop unrolling can result in further time savings, but not necessarily** so, as the Java measurement shows.

Loops – Unrolling

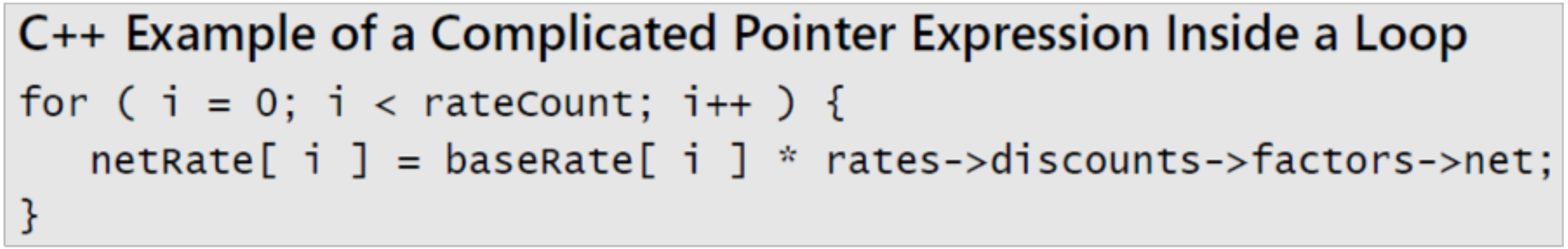
- When you look at the previous code, you might not think it looks incredibly complicated, but when you see the performance gain, you can appreciate the tradeoff between performance and readability.

Loops – Minimizing the Work Inside Loops

- One key to writing effective loops is to minimize the work done inside a loop.
- If you can evaluate a statement or part of a statement outside a loop so that only the result is used inside the loop, do so.
- It’s good programming practice, and **in some cases it improves readability**.

Loops – Minimizing the Work Inside Loops

- Suppose you have a complicated pointer expression inside a loop:

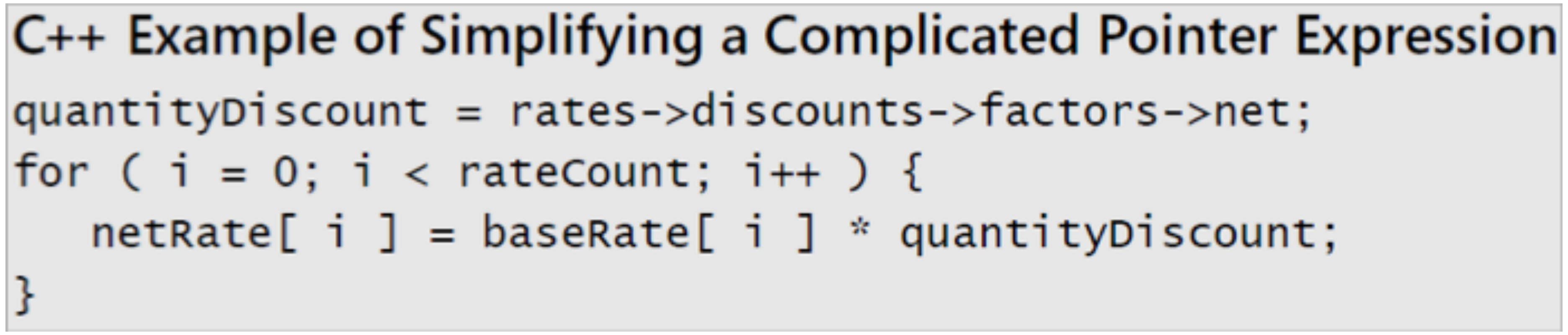


C++ Example of a Complicated Pointer Expression Inside a Loop

```
for ( i = 0; i < rateCount; i++ ) {
   netRate[ i ] = baseRate[ i ] * rates->discounts->factors->net;
}
```

Loops – Minimizing the Work Inside Loops

- In this case, assigning the complicated pointer expression to a well-named variable improves readability and often improves performance.



C++ Example of Simplifying a Complicated Pointer Expression

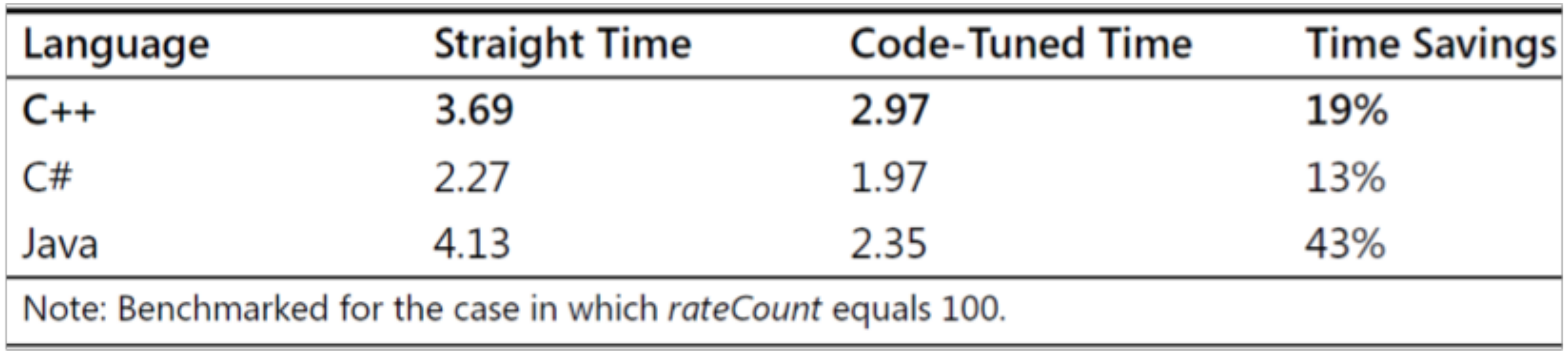
```
quantityDiscount = rates->discounts->factors->net;
for ( i = 0; i < rateCount; i++ ) {
   netRate[ i ] = baseRate[ i ] * quantityDiscount;
}
```

Loops – Minimizing the Work Inside Loops

- The extra variable, *quantityDiscount*, makes it clear that the *baseRate* array is being multiplied by a quantity-discount factor to compute the net rate.
- That wasn't at all clear from the original expression in the loop.
- Putting the complicated pointer expression into a variable outside the loop also saves the pointer accesses for each pass through the loop, resulting in the following savings:

Loops – Minimizing the Work Inside Loops

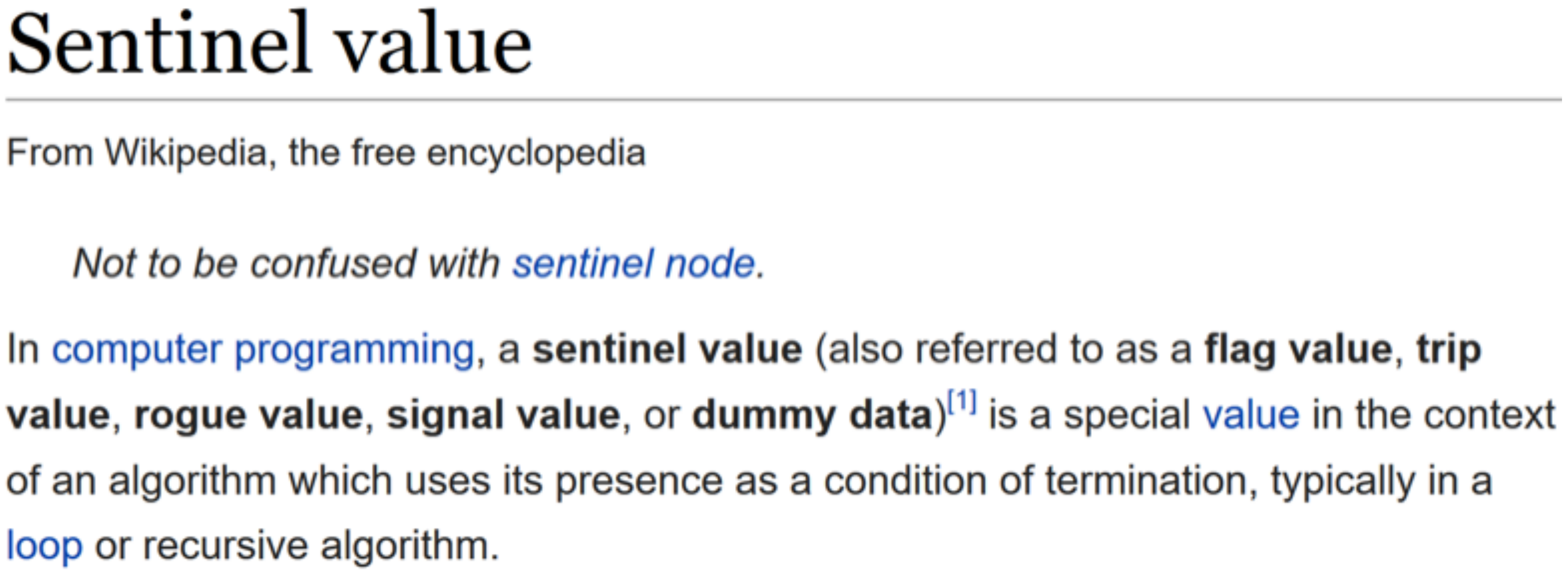
- Java provides great improvement



Language	Straight Time	Code-Tuned Time	Time Savings
C++	**3.69**	**2.97**	**19%**
C#	2.27	1.97	13%
Java	4.13	2.35	43%

Note: Benchmarked for the case in which *rateCount* equals 100.

Loops – Sentinel Values



Sentinel value

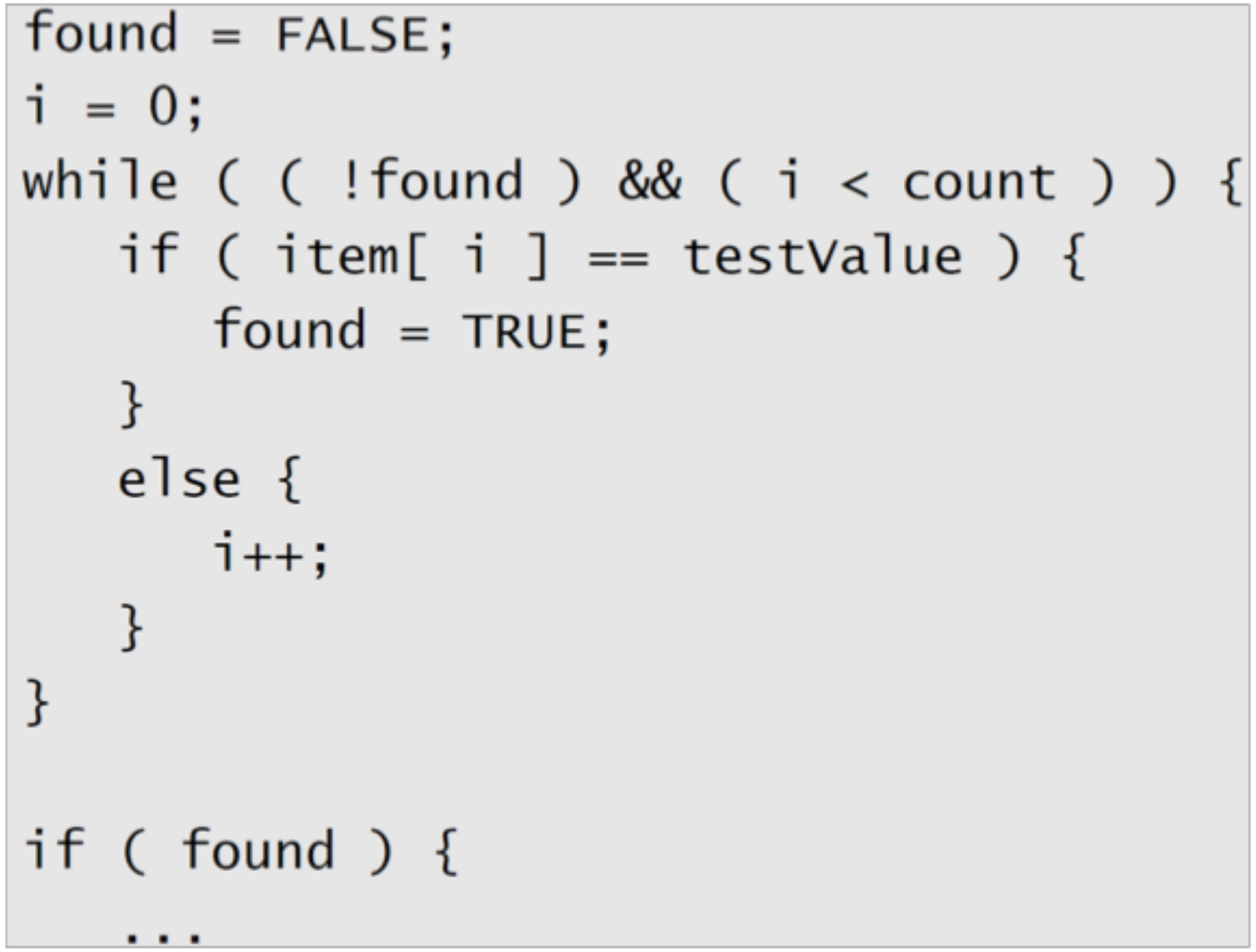
From Wikipedia, the free encyclopedia

Not to be confused with sentinel node.

In computer programming, a **sentinel value** (also referred to as a **flag value**, **trip value**, **rogue value**, **signal value**, or **dummy data**)[1] is a special value in the context of an algorithm which uses its presence as a condition of termination, typically in a loop or recursive algorithm.

Loops – Sentinel Values

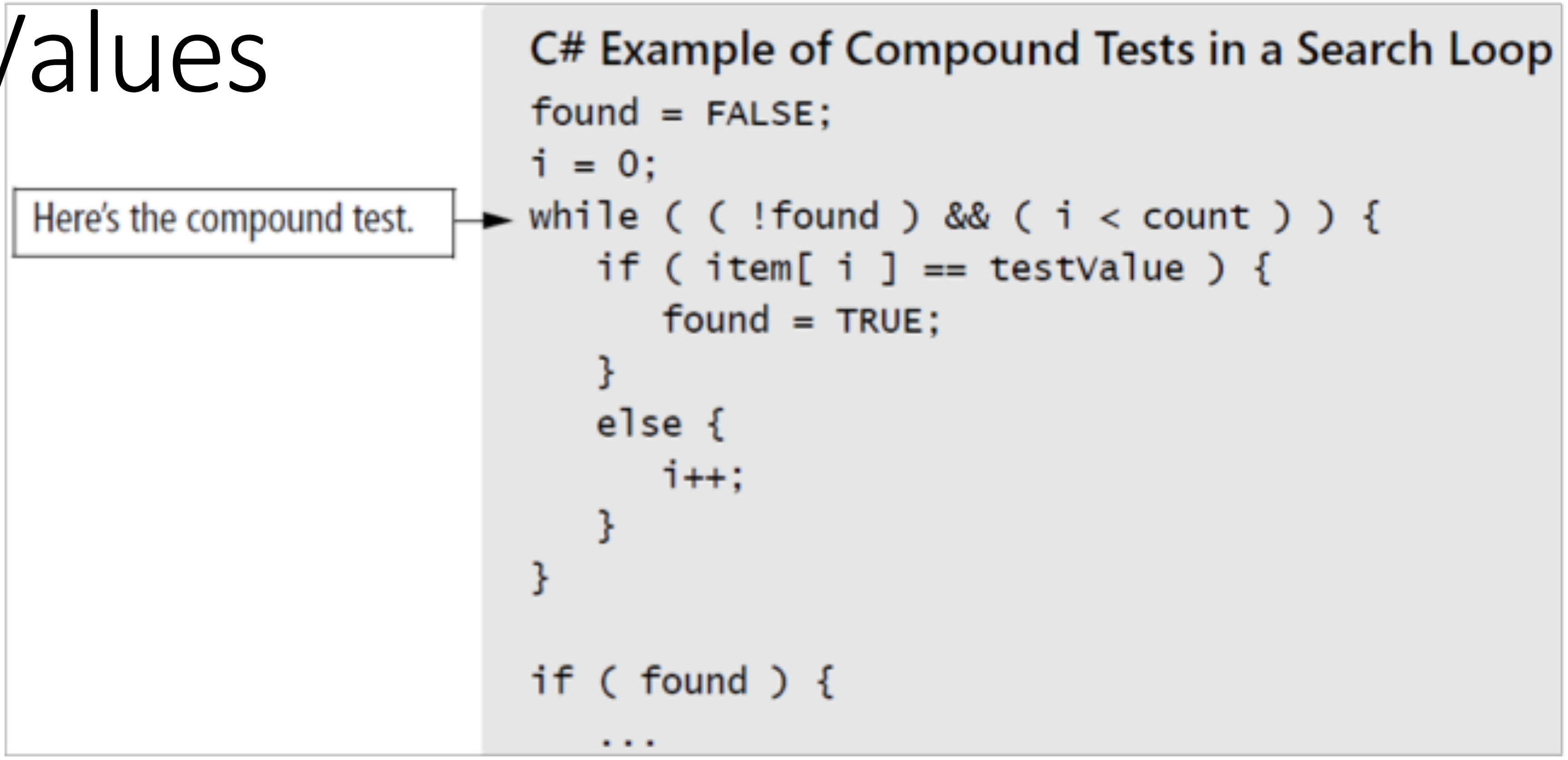
- **Anything wrong?**



```
found = FALSE;
i = 0;
while ( ( !found ) && ( i < count ) ) {
   if ( item[ i ] == testValue ) {
      found = TRUE;
   }
   else {
      i++;
   }
}

if ( found ) {
   ...
```

Loops – Sentinel Values

- In this code, each iteration of the loop tests for *!found* and for *i < count*.
- The purpose of the *!found* test is to determine when the desired element has been found.
- The purpose of the *i < count* test is to avoid running past the end of the array. Inside the loop, each value of *item[]* is tested individually, so the loop really has three tests for each iteration.


C# Example of Compound Tests in a Search Loop

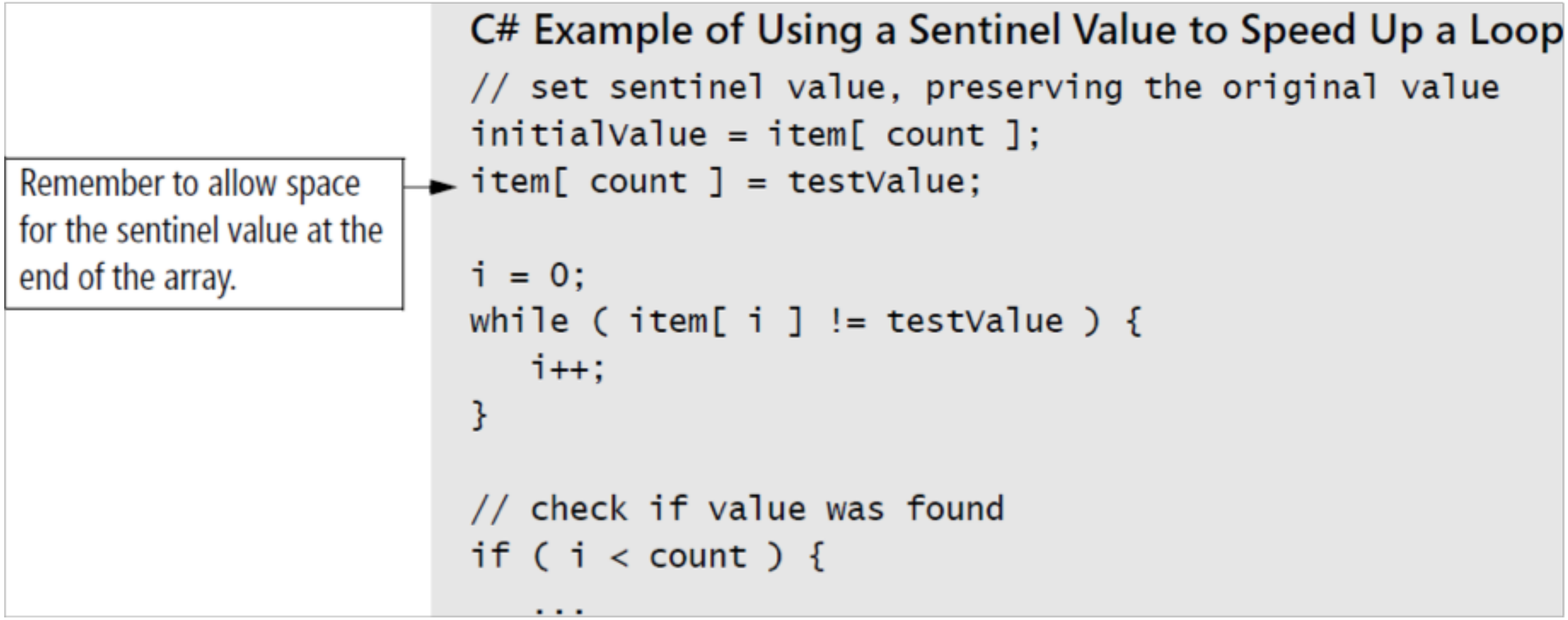
Here's the compound test.

```
found = FALSE;
i = 0;
while ( ( !found ) && ( i < count ) ) {
   if ( item[ i ] == testValue ) {
      found = TRUE;
   }
   else {
      i++;
   }
}

if ( found ) {
   ...
```

Loops – Sentinel Values

- In this kind of search loop, **you can combine the three tests so that you test only once per iteration by putting a “sentinel” at the end of the search range to stop the loop**.
- In this case, you can simply assign the value you’re looking for to the element just beyond the end of the search range. (Remember to leave space for that element when you declare the array.)
- You then check each element, and if you don’t find the element until you find the one you stuck at the end, you know that the value you’re looking for isn’t really there.

Loops – Sentinel Values

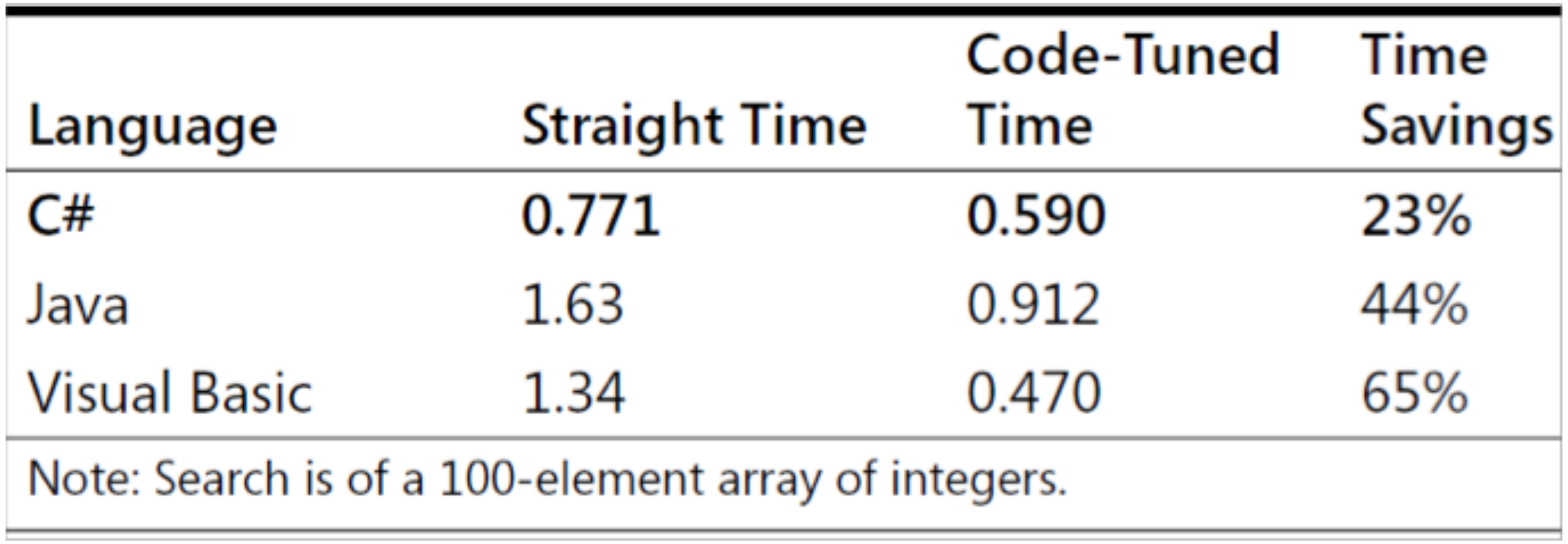

Remember to allow space for the sentinel value at the end of the array.

C# Example of Using a Sentinel Value to Speed Up a Loop

```
// set sentinel value, preserving the original value
initialValue = item[ count ];
item[ count ] = testValue;

i = 0;
while ( item[ i ] != testValue ) {
   i++;
}

// check if value was found
if ( i < count ) {
   ...
```

Loops – Sentinel Values

- When *item* is an array of **integers**, the savings can be dramatic:

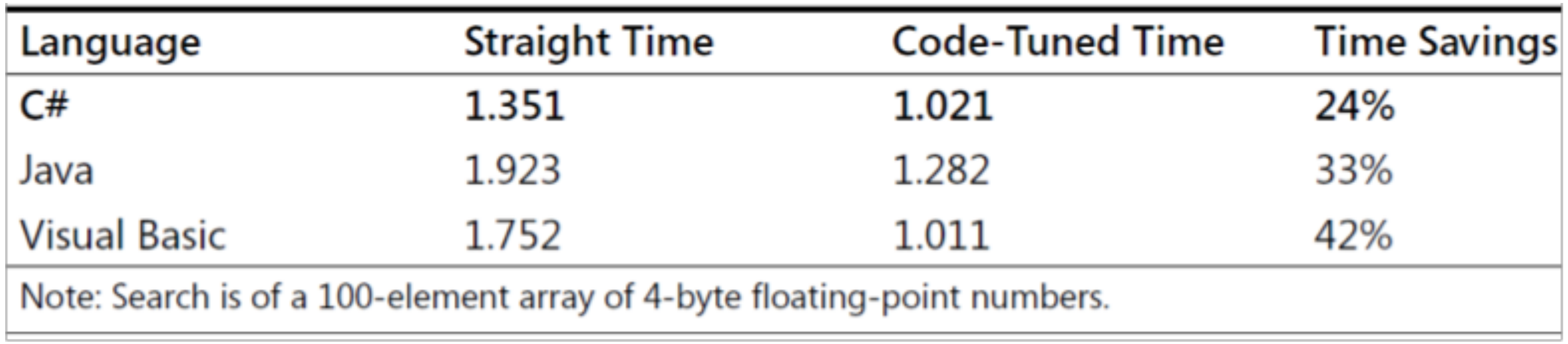


Language	Straight Time	Code-Tuned Time	Time Savings
C#	0.771	0.590	23%
Java	1.63	0.912	44%
Visual Basic	1.34	0.470	65%

Note: Search is of a 100-element array of integers.

Loops – Sentinel Values

- The Visual Basic results are particularly dramatic, but all the results are good. *When the kind of array changes, however, the results also change*.
- When *item* is an array of single-precision floating-point numbers, the results are as follows:



Language	Straight Time	Code-Tuned Time	Time Savings
C#	**1.351**	**1.021**	**24%**
Java	1.923	1.282	33%
Visual Basic	1.752	1.011	42%

Note: Search is of a 100-element array of 4-byte floating-point numbers.

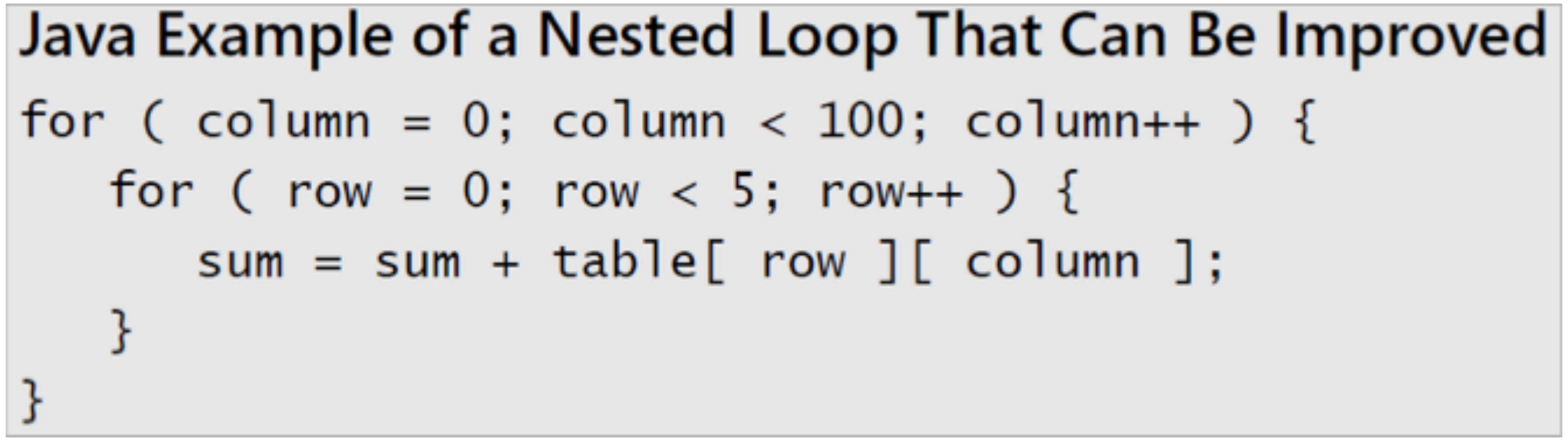
Loops

- The total number of loop executions?

```
for ( column = 0; column < 100; column++ ) {
    for ( row = 0; row < 5; row++ ) {
        sum = sum + table[ row ][ column ];
    }
}
```

Loops – Putting the Busiest Loop on the Inside

- When you have nested loops, think about which loop you want on the outside and which you want on the inside. Following is an example of a nested loop that can be improved:

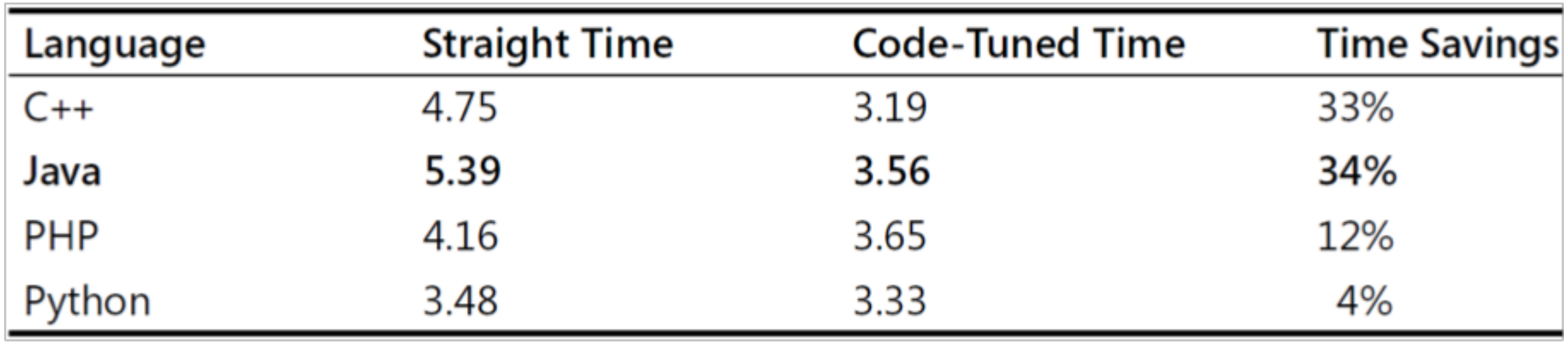


Java Example of a Nested Loop That Can Be Improved

```
for ( column = 0; column < 100; column++ ) {
   for ( row = 0; row < 5; row++ ) {
      sum = sum + table[ row ][ column ];
   }
}
```

Loops – Putting the Busiest Loop on the Inside

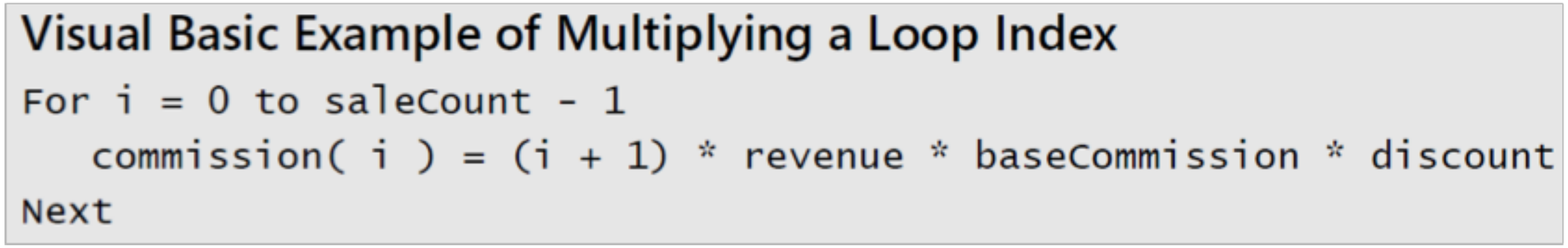
- The key to improving the loop is that the outer loop executes much more often than the inner loop.
- Each time the loop executes, it has to initialize the loop index, increment it on each pass through the loop, and check it after each pass.



Language	Straight Time	Code-Tuned Time	Time Savings
C++	4.75	3.19	33%
Java	**5.39**	**3.56**	**34%**
PHP	4.16	3.65	12%
Python	3.48	3.33	4%

Loops

- Any comments on the performance?
- How can we run it faster?



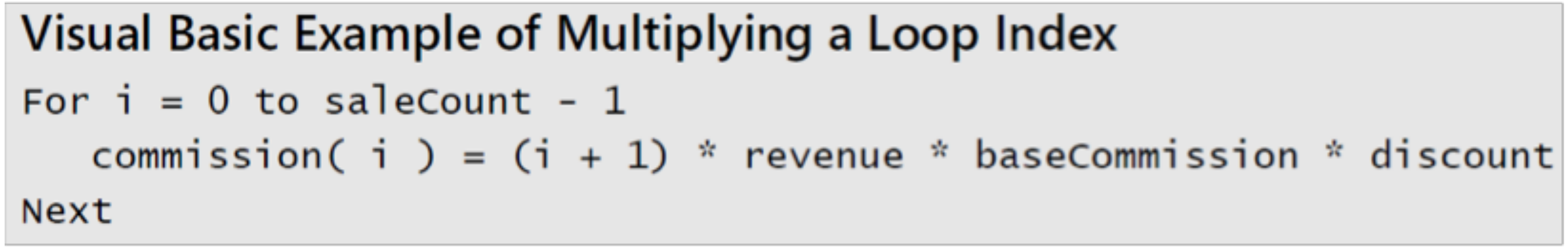
Visual Basic Example of Multiplying a Loop Index

```
For i = 0 to saleCount - 1
   commission( i ) = (i + 1) * revenue * baseCommission * discount
Next
```

Loops – Strength Reduction

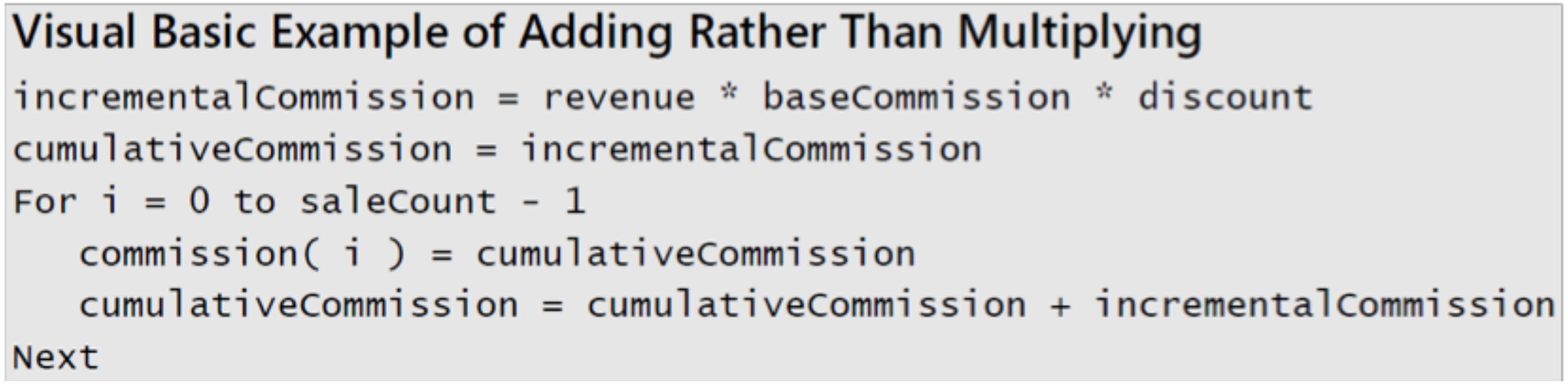
- Reducing strength means replacing an expensive operation such as multiplication with a cheaper operation such as addition.
- Sometimes you’ll have an expression inside a loop that depends on multiplying the loop index by a factor.
- Addition is usually faster than multiplication, and if you can compute the same number by adding the amount on each iteration of the loop rather than by multiplying, the code will typically run faster.

Loops – Strength Reduction



Visual Basic Example of Multiplying a Loop Index

```
For i = 0 to saleCount - 1
   commission( i ) = (i + 1) * revenue * baseCommission * discount
Next
```

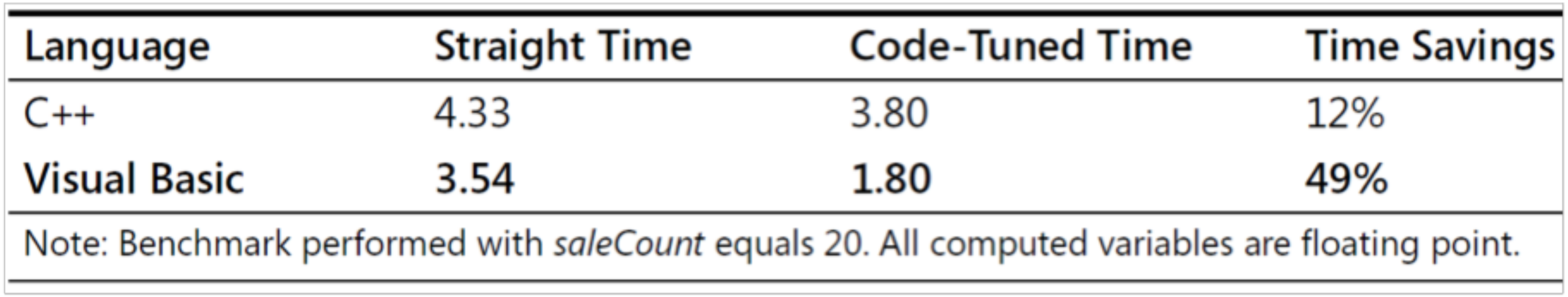


Visual Basic Example of Adding Rather Than Multiplying

```
incrementalCommission = revenue * baseCommission * discount
cumulativeCommission = incrementalCommission
For i = 0 to saleCount - 1
   commission( i ) = cumulativeCommission
   cumulativeCommission = cumulativeCommission + incrementalCommission
Next
```

Loops – Strength Reduction

- The key is that the original multiplication has to depend on the loop index. In this case, the loop index was the only part of the expression that varied, so the expression could be recoded more economically.



Language	Straight Time	Code-Tuned Time	Time Savings
C++	4.33	3.80	12%
Visual Basic	**3.54**	**1.80**	**49%**

Note: Benchmark performed with *saleCount* equals 20. All computed variables are floating point.

Outline

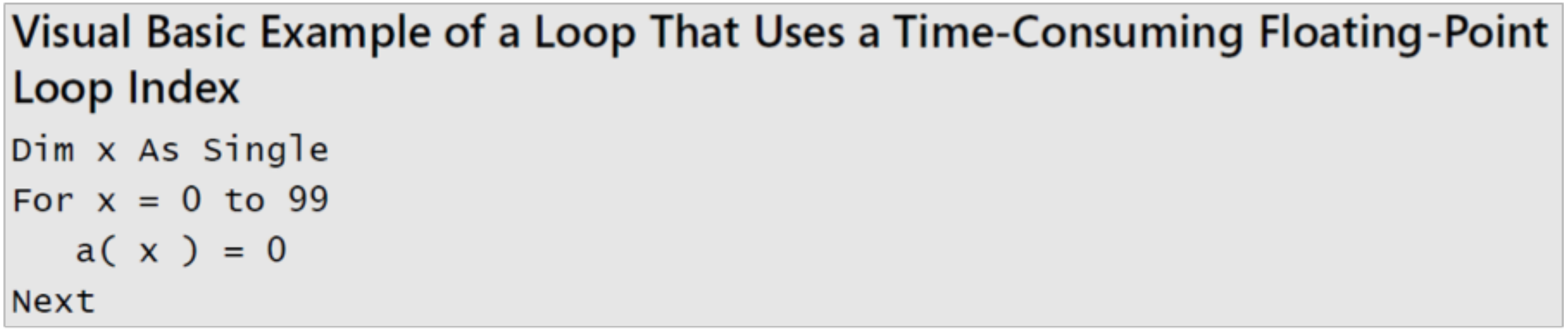
- Logic
- Loops
- Data Transformations
- Expressions

Data Transformations

- Changes in data types can be a powerful aid in reducing program size and improving execution speed.
- Data-structure design is outside the scope of this course, but modest changes in the implementation of a specific data type can also improve performance.
- Here are a few ways to tune your data types.

Data Transformations – Integers over Floats

- Integer addition and multiplication tend to be faster than floating point.
- Changing a loop index from a floating point to an integer, for example, can save time:

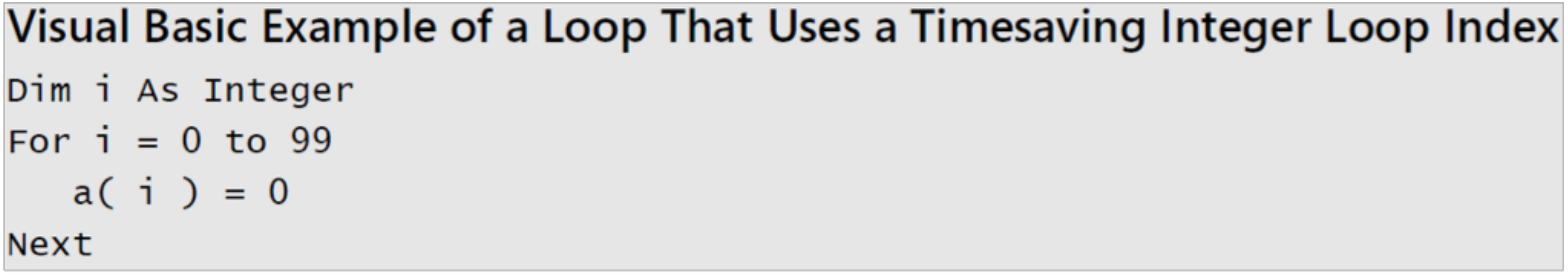


Visual Basic Example of a Loop That Uses a Time-Consuming Floating-Point Loop Index

```
Dim x As Single
For x = 0 to 99
   a( x ) = 0
Next
```

Data Transformations – Integers over Floats

- Contrast this with a similar Visual Basic loop that explicitly uses the integer type:

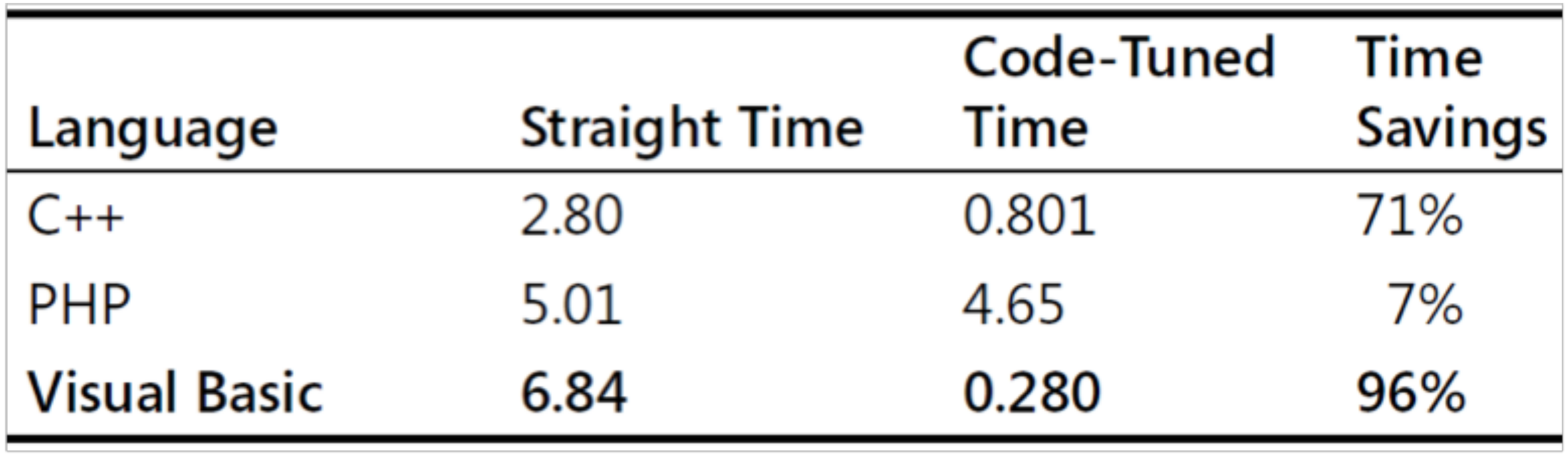


Visual Basic Example of a Loop That Uses a Timesaving Integer Loop Index

```
Dim i As Integer
For i = 0 to 99
   a( i ) = 0
Next
```

Data Transformations – Integers over Floats

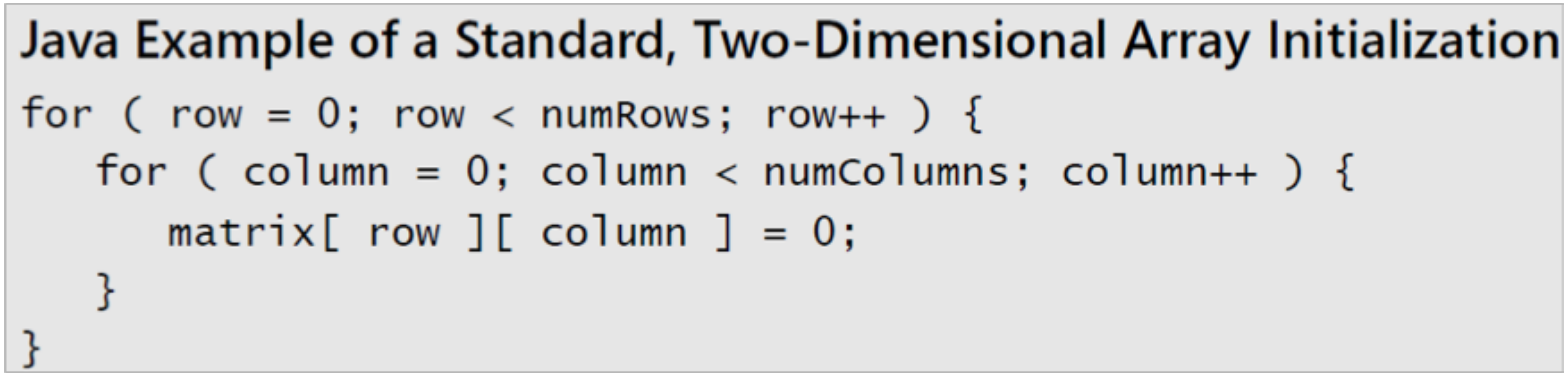
- How much difference does it make? Here are the results for this Visual Basic code and for similar code in C++ and PHP:



Language	Straight Time	Code-Tuned Time	Time Savings
C++	2.80	0.801	71%
PHP	5.01	4.65	7%
Visual Basic	**6.84**	**0.280**	**96%**

Data Transformations

- How can we change and use this 2D array as 1D?

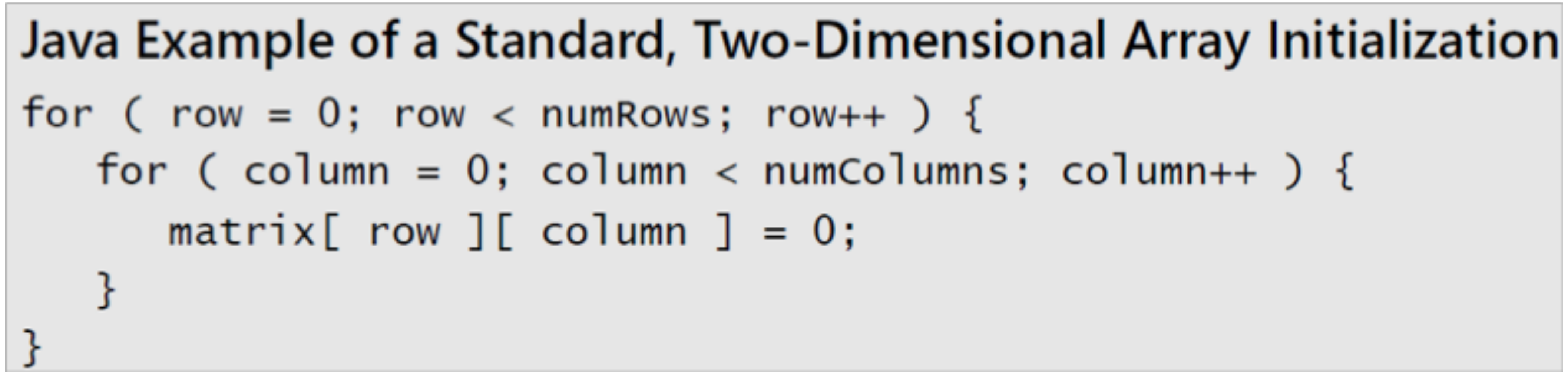


Java Example of a Standard, Two-Dimensional Array Initialization

```
for ( row = 0; row < numRows; row++ ) {
   for ( column = 0; column < numColumns; column++ ) {
      matrix[ row ][ column ] = 0;
   }
}
```

Data Transformations – Fewer Array Dims

- Multiple dimensions on arrays are expensive.
- If you can structure your data so that it's in a one-dimensional array rather than a two-dimensional or three-dimensional array, you might be able to save some time.
- Suppose you have initialization code like this:

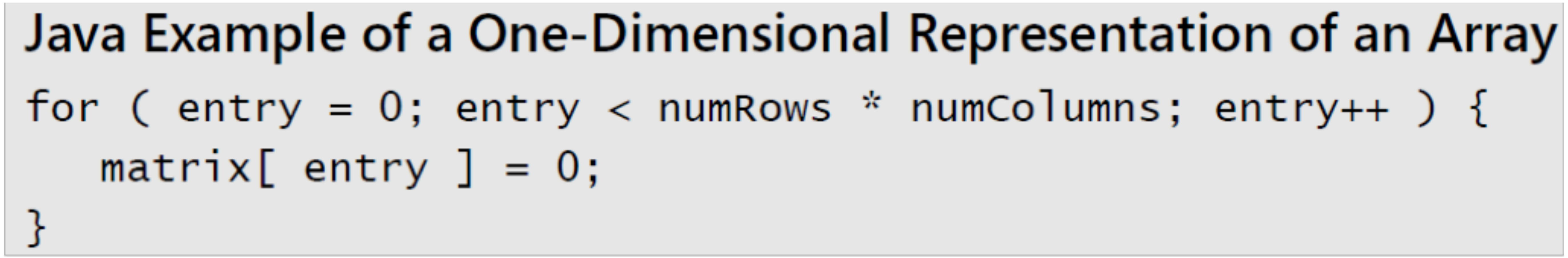


Java Example of a Standard, Two-Dimensional Array Initialization

```
for ( row = 0; row < numRows; row++ ) {
   for ( column = 0; column < numColumns; column++ ) {
      matrix[ row ][ column ] = 0;
   }
}
```

Data Transformations – Fewer Array Dims

- When this code is run with 50 rows and 20 columns, it takes twice as long with a Java compiler as when the array is restructured so that it's one-dimensional.

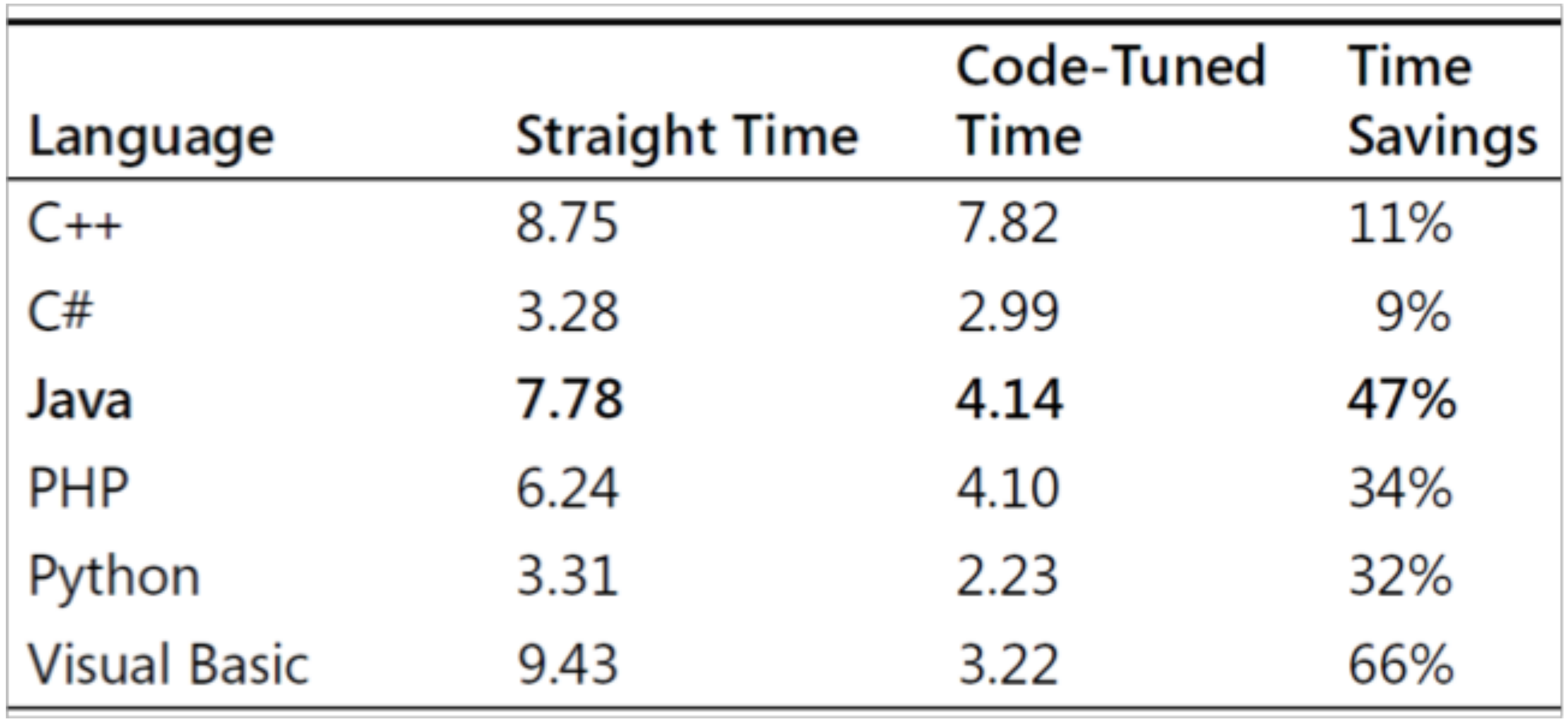


Java Example of a One-Dimensional Representation of an Array

```
for ( entry = 0; entry < numRows * numColumns; entry++ ) {
   matrix[ entry ] = 0;
}
```

Data Transformations – Fewer Array Dims

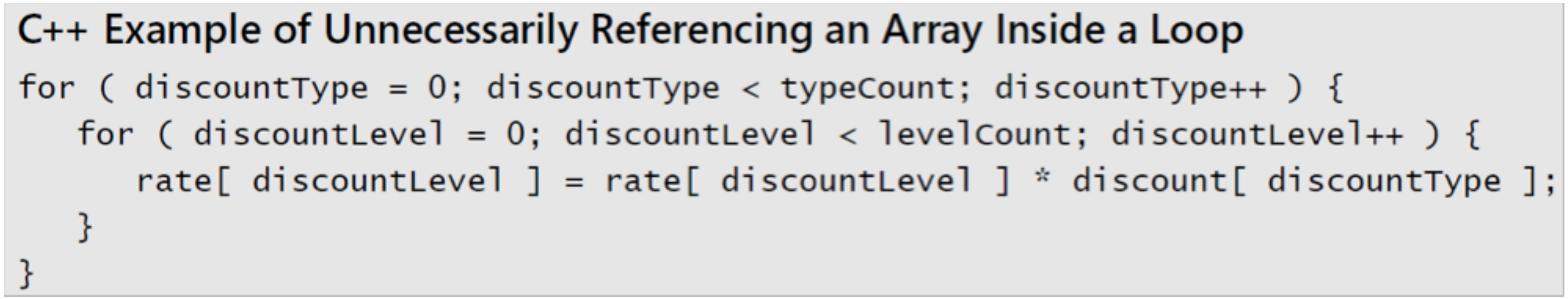
- Here's a summary of the results, with the addition of comparable results in several other languages:



Language	Straight Time	Code-Tuned Time	Time Savings
C++	8.75	7.82	11%
C#	3.28	2.99	9%
Java	**7.78**	**4.14**	**47%**
PHP	6.24	4.10	34%
Python	3.31	2.23	32%
Visual Basic	9.43	3.22	66%

Data Transformations – Less Array Refs

- In addition to minimizing accesses to doubly or triply dimensioned arrays, it’s often advantageous to minimize array accesses.
- A loop that repeatedly uses one element of an array is a good candidate for the application of this technique.

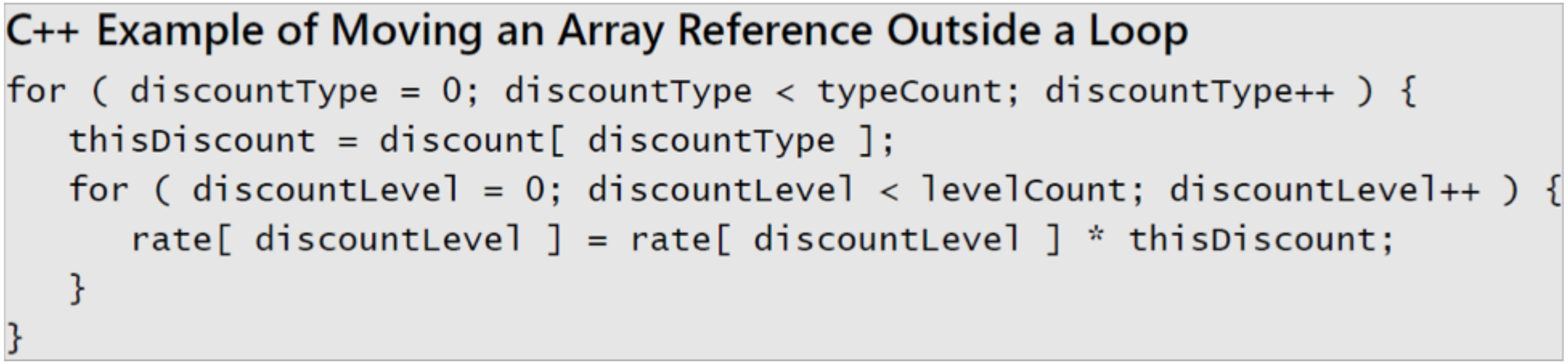


C++ Example of Unnecessarily Referencing an Array Inside a Loop

```
for ( discountType = 0; discountType < typeCount; discountType++ ) {
   for ( discountLevel = 0; discountLevel < levelCount; discountLevel++ ) {
      rate[ discountLevel ] = rate[ discountLevel ] * discount[ discountType ];
   }
}
```

Data Transformations – Less Array Refs

- The reference to *discount[discountType]* doesn’t change when *discountLevel* changes in the inner loop.
- Consequently, you can move it out of the inner loop so that you’ll have only one array access per execution of the outer loop rather than one for each execution of the inner loop.

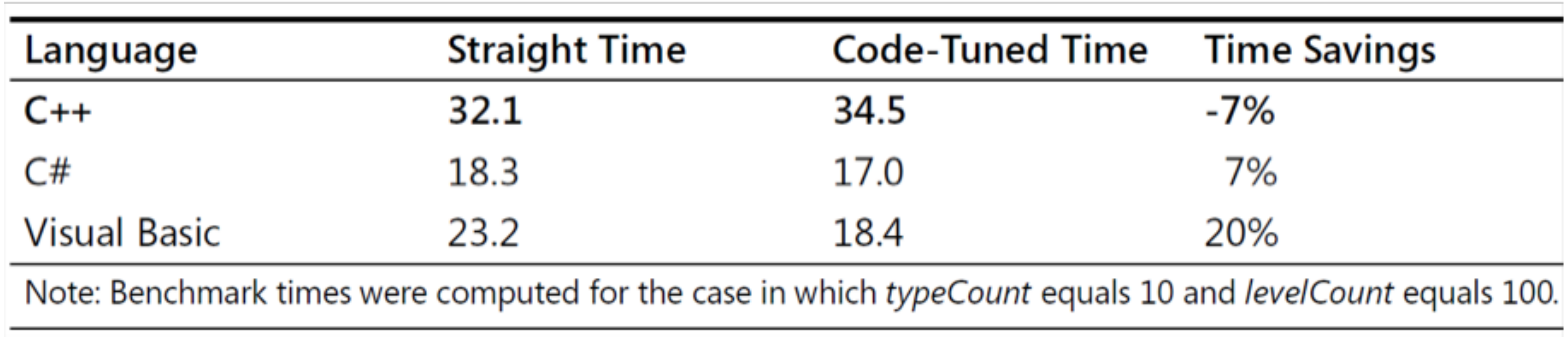


C++ Example of Moving an Array Reference Outside a Loop

```
for ( discountType = 0; discountType < typeCount; discountType++ ) {
   thisDiscount = discount[ discountType ];
   for ( discountLevel = 0; discountLevel < levelCount; discountLevel++ ) {
      rate[ discountLevel ] = rate[ discountLevel ] * thisDiscount;
   }
}
```

Data Transformations – Less Array Refs

- Results vary significantly from compiler to compiler.



Language	Straight Time	Code-Tuned Time	Time Savings
C++	**32.1**	**34.5**	-7%
C#	18.3	17.0	7%
Visual Basic	23.2	18.4	20%

Note: Benchmark times were computed for the case in which *typeCount* equals 10 and *levelCount* equals 100.

Data Transformations – Use Supplm Indexes

- Using a supplementary index means adding related data that makes accessing a data type more efficient.
- You can add the related data to the main data type, or you can store it in a parallel structure

Data Transformations – Use Supplm Indexes

- **String-Length Index**
- One example of using a supplementary index can be found in the different string-storage strategies.
- In C, strings are terminated by a byte that's set to 0.
  - To determine the length of a string in C, a program has to start at the beginning of the string and count each byte until it finds the byte that's set to 0.
- In Visual Basic string format, a length byte hidden at the beginning of each string indicates how long the string is.
  - To determine the length of a Visual Basic string, the program just looks at the length byte. Visual Basic length byte is an example of augmenting a data type with an index to make certain operations—like computing the length of a string—faster.

Data Transformations – Use Supplm Indexes

- **String-Length Index**
- You can apply the idea of indexing for length to any variable-length data type.
- It’s often more efficient to keep track of the length of the structure rather than computing the length each time you need it.

Data Transformations – Use Caching

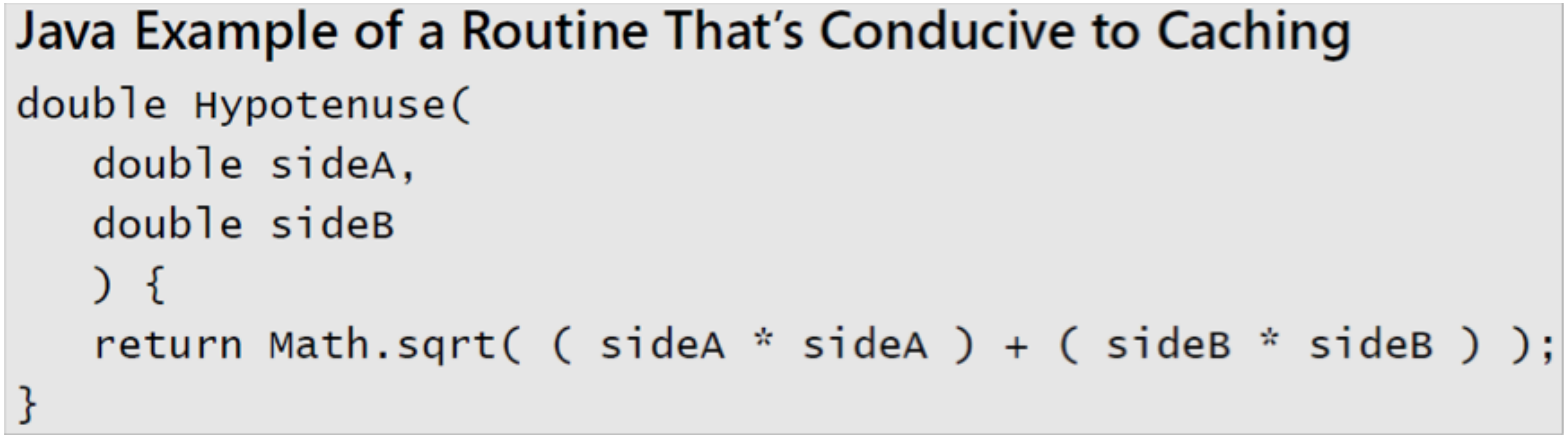
- Caching means saving a few values in such a way that you can retrieve the most commonly used values more easily than the less commonly used values.
- If a program randomly reads records from a disk, for example, a routine might use a cache to save the records read most frequently.
- When the routine receives a request for a record, it checks the cache to see whether it has the record. If it does, the record is returned directly from memory rather than from disk.

Data Transformations – Use Caching

- In addition to caching records on disk, you can apply caching in other areas.
- In a Microsoft Windows font-proofing program, the performance bottleneck was in retrieving the width of each character as it was displayed.
- Caching the most recently used character width roughly doubled the display speed

Data Transformations – Use Caching

- You can cache the results of time-consuming computations too—especially if the parameters to the calculation are simple.
- Suppose, <u>for example</u>, that you need to compute the length of the hypotenuse of a right triangle, given the lengths of the other two sides. The straightforward implementation:

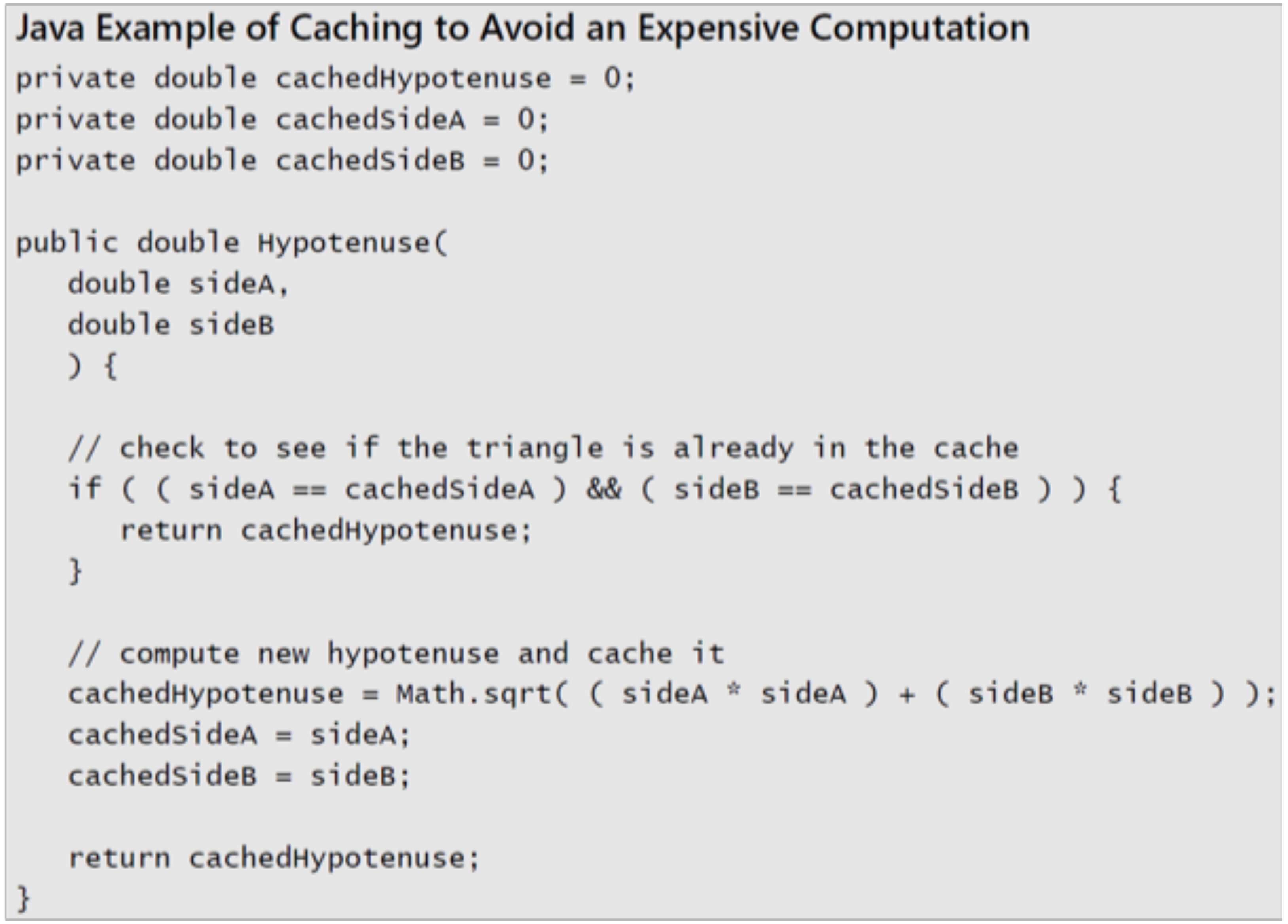


Java Example of a Routine That's Conducive to Caching

```
double Hypotenuse(
   double sideA,
   double sideB
   ) {
   return Math.sqrt( ( sideA * sideA ) + ( sideB * sideB ) );
}
```

Data Transformations – Use Caching

- If you know that the same values tend to be requested repeatedly, you can cache values this way:

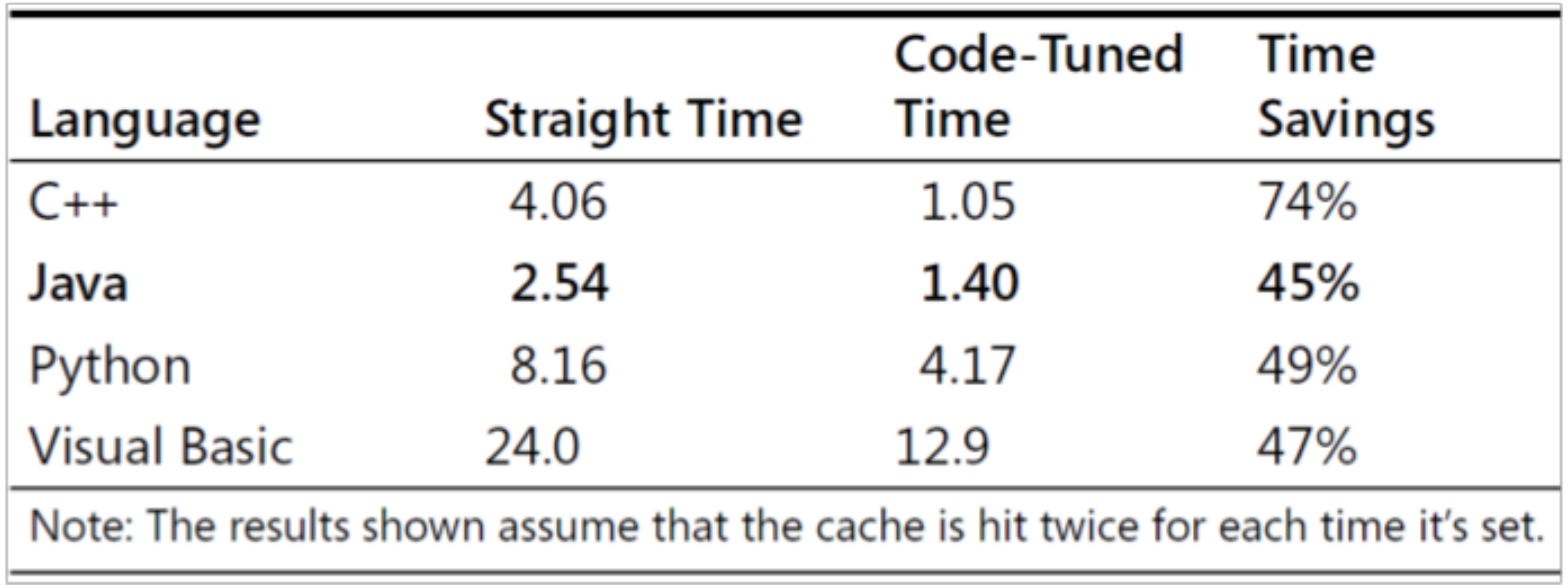


Java Example of Caching to Avoid an Expensive Computation

```
private double cachedHypotenuse = 0;
private double cachedSideA = 0;
private double cachedSideB = 0;

public double Hypotenuse(
   double sideA,
   double sideB
   ) {

   // check to see if the triangle is already in the cache
   if ( ( sideA == cachedSideA ) && ( sideB == cachedSideB ) ) {
      return cachedHypotenuse;
   }

   // compute new hypotenuse and cache it
   cachedHypotenuse = Math.sqrt( ( sideA * sideA ) + ( sideB * sideB ) );
   cachedSideA = sideA;
   cachedSideB = sideB;

   return cachedHypotenuse;
}
```

Data Transformations – Use Caching

- The second version of the routine is more complicated than the first and takes up more space, so speed has to be at a premium to justify it. Many caching schemes cache more than one element, so they have even more overhead. Here's the speed difference:



Language	Straight Time	Code-Tuned Time	Time Savings
C++	4.06	1.05	74%
Java	**2.54**	**1.40**	**45%**
Python	8.16	4.17	49%
Visual Basic	24.0	12.9	47%

Note: The results shown assume that the cache is hit twice for each time it's set.

Data Transformations – Use Caching

- The success of the cache depends on the relative costs of accessing a cached element, creating an uncached element, and saving a new element in the cache.
- Success also depends on how often the cached information is requested. In some cases, success might also depend on caching done by the hardware.
- Generally, the more it costs to generate a new element and the more times the same information is requested, the more valuable a cache is. The cheaper it is to access a cached element and save new elements in the cache, the more valuable a cache is.
- As with other optimization techniques, caching adds complexity and tends to be error-prone.

Outline

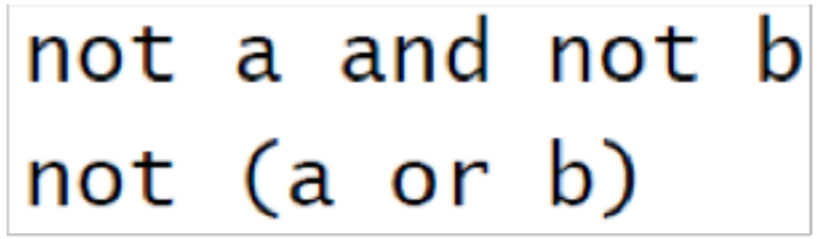
- Logic
- Loops
- Data Transformations
- Expressions

Expressions

- Much of the work in a program is done inside mathematical or logical expressions.
- Complicated expressions tend to be expensive, so this section looks at ways to make them cheaper.

Expressions - Exploit Algebraic Identities

- You can use algebraic identities to replace costly operations with cheaper ones.
- For example, the following expressions are logically equivalent:

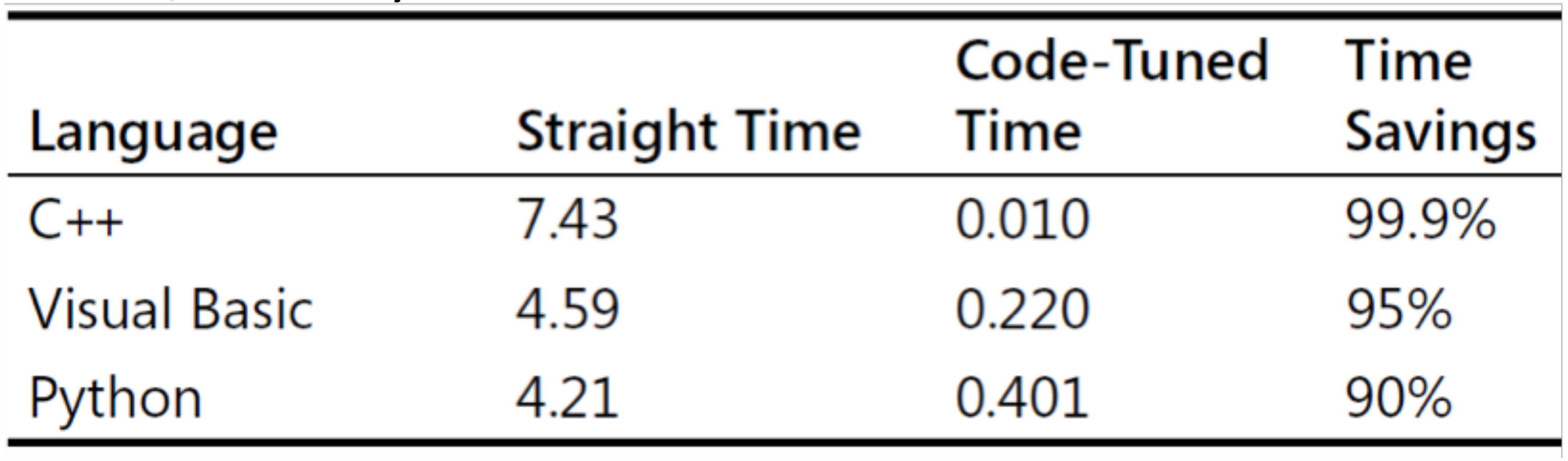


```
not a and not b
not (a or b)
```

- If you choose the second expression instead of the first, you can save a *not* operation.
- Although the savings from avoiding a single *not* operation are probably inconsequential, the general principle is powerful.

Expressions - Exploit Algebraic Identities

- For example, a program on whether *sqrt(x) < sqrt(y).* Since *sqrt(x)* is less than *sqrt(y)* only when *x* is less than *y*, you can replace the first test with *x < y*.
- Given the cost of the *sqrt()* routine, you'd expect the savings to be dramatic, and they are. Here are the results:



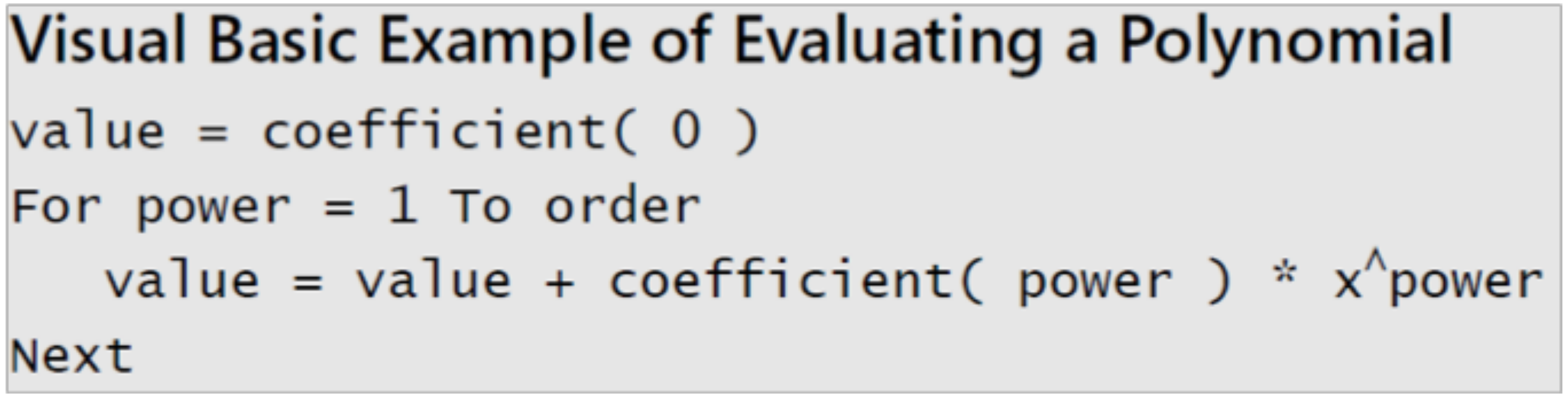
Language	Straight Time	Code-Tuned Time	Time Savings
C++	7.43	0.010	99.9%
Visual Basic	4.59	0.220	95%
Python	4.21	0.401	90%

Expressions - Use Strength Reduction

- Strength reduction means replacing an expensive operation with a cheaper one. Here are some possible substitutions:
  - Replace multiplication with addition.
  - Replace exponentiation with multiplication.
  - Replace floating-point numbers with fixed-point numbers or integers.
  - Replace double-precision floating points with single-precision numbers.
  - Replace integer multiplication-by-two and division-by-two with shift operations.

Expressions - Use Strength Reduction

- Suppose you have to evaluate a polynomial. If you’re rusty on polynomials, they’re the things that look like A*x*2 + B*x* + C.
- The letters *A, B,* and *C* are coefficients, and *x* is a variable. General code to evaluate an *n*th-order polynomial looks like this:

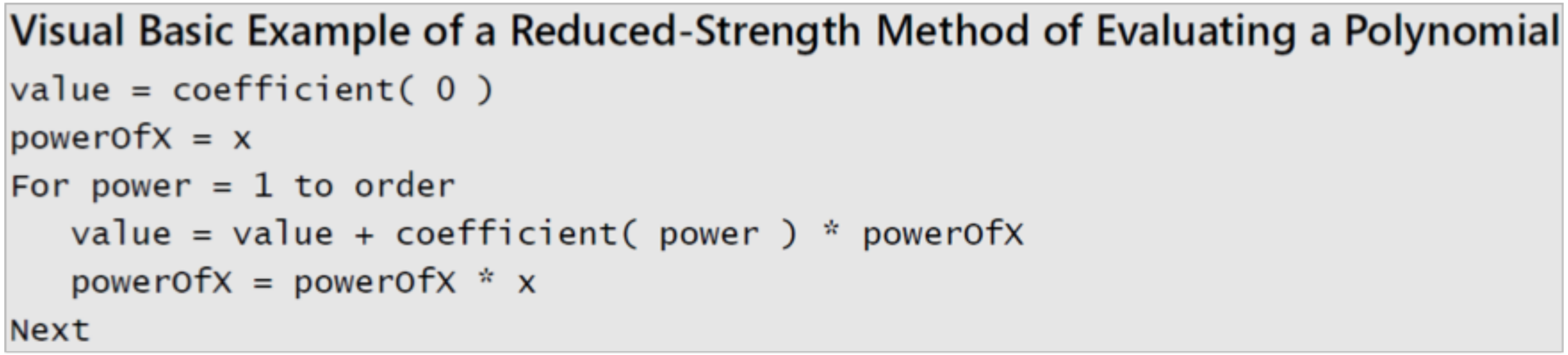


Visual Basic Example of Evaluating a Polynomial

```
value = coefficient( 0 )
For power = 1 To order
   value = value + coefficient( power ) * x^power
Next
```

Expressions - Use Strength Reduction

- One solution would be to replace the exponentiation with a multiplication on each pass through the loop, which is analogous to the strength-reduction case a few sections ago in which a multiplication was replaced with an addition.

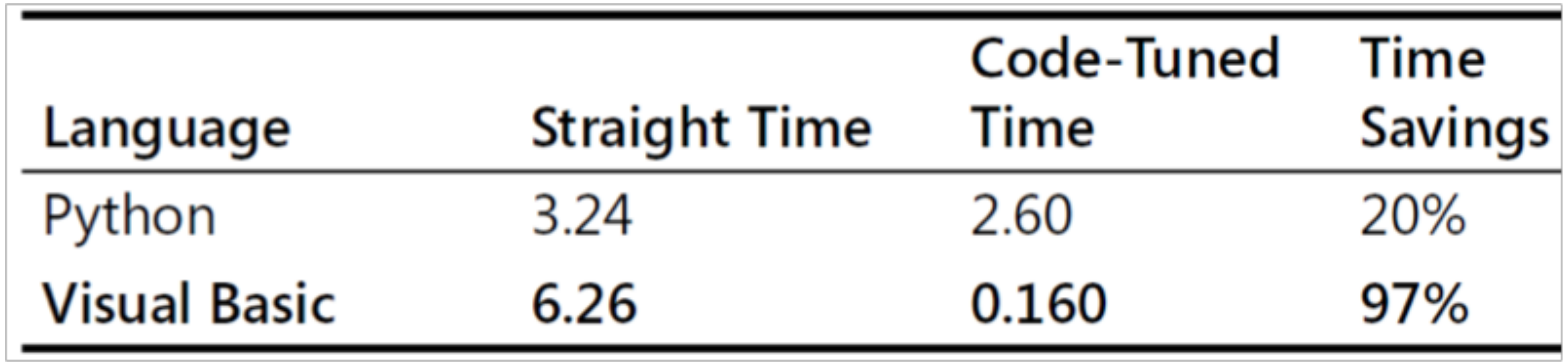


Visual Basic Example of a Reduced-Strength Method of Evaluating a Polynomial

```
value = coefficient( 0 )
powerOfX = x
For power = 1 to order
   value = value + coefficient( power ) * powerOfX
   powerOfX = powerOfX * x
Next
```

Expressions - Use Strength Reduction

- This produces a noticeable advantage if you're working with second-order polynomials—that is, polynomials in which the highest-power term is squared—or higher-order polynomials:



Language	Straight Time	Code-Tuned Time	Time Savings
Python	3.24	2.60	20%
Visual Basic	**6.26**	**0.160**	**97%**

Expressions

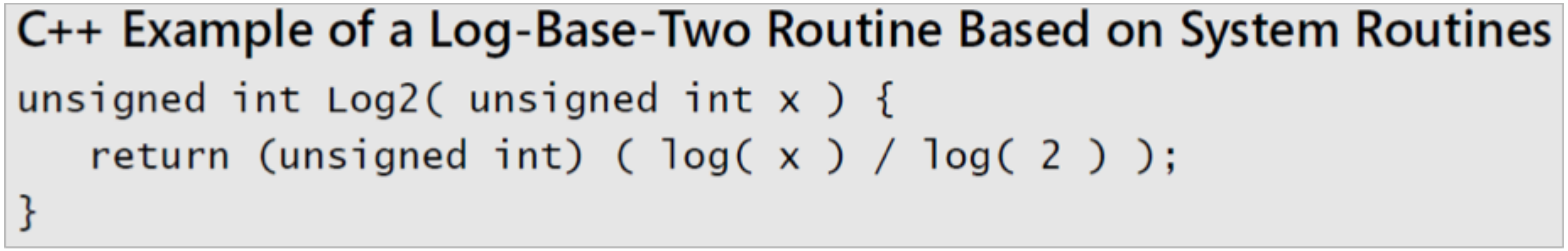
- Compute the base-two logarithm of an integer, truncated to the nearest integer.

```
unsigned int Log2( unsigned int x ) {
   return (unsigned int) ( log( x ) / log( 2 ) );
}
```

- **Any suggestion to improve its performance?**

Expressions - Initialize at Compile Time

- If you're using a named **constant** or a magic number in a routine call and it's the only argument, that's a clue that you could **precompute** the number, put it into a constant, and avoid the routine call.
- The same principle applies to multiplications, divisions, additions, and other operations.
- For example, compute the base-two logarithm of an integer, truncated to the nearest integer. If the system doesn't have a log-base-two routine, a quick and easy approach:

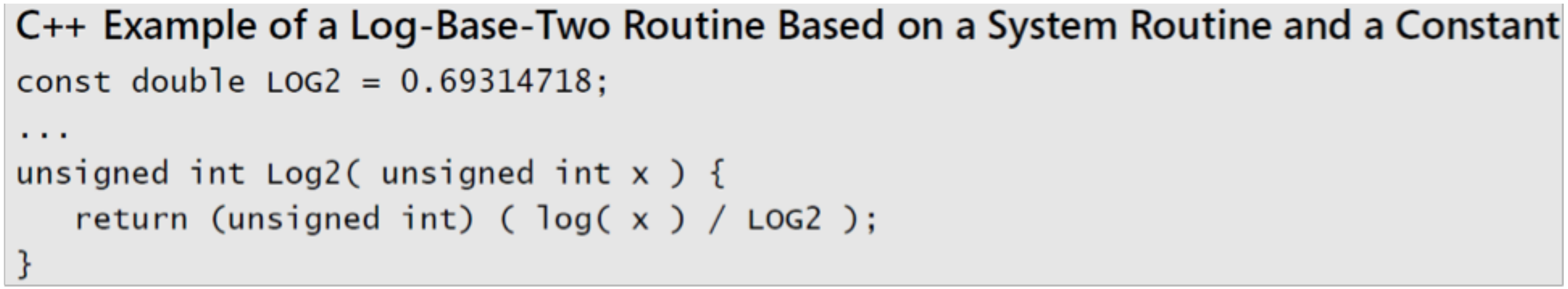


C++ Example of a Log-Base-Two Routine Based on System Routines

```
unsigned int Log2( unsigned int x ) {
   return (unsigned int) ( log( x ) / log( 2 ) );
}
```

Expressions - Initialize at Compile Time

- This routine is very slow, and because the value of *log(2)* never changed, replace *log(2)* with its computed value, *0.69314718*, like this:

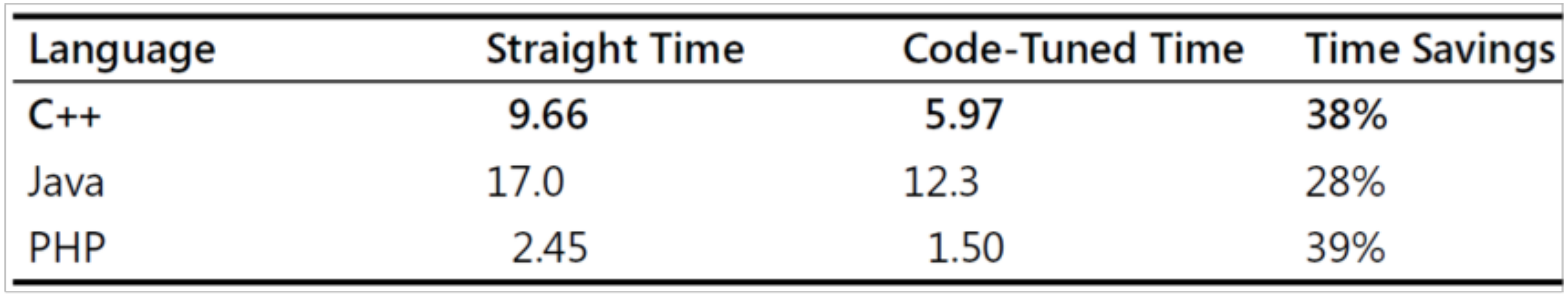


C++ Example of a Log-Base-Two Routine Based on a System Routine and a Constant

```
const double LOG2 = 0.69314718;
...
unsigned int Log2( unsigned int x ) {
   return (unsigned int) ( log( x ) / LOG2 );
}
```

Expressions - Initialize at Compile Time

- Since *log()* tends to be an expensive routine—much more expensive than type conversions or division—you’d expect that cutting the calls to the *log()* function by half would cut the time required for the routine by about half.



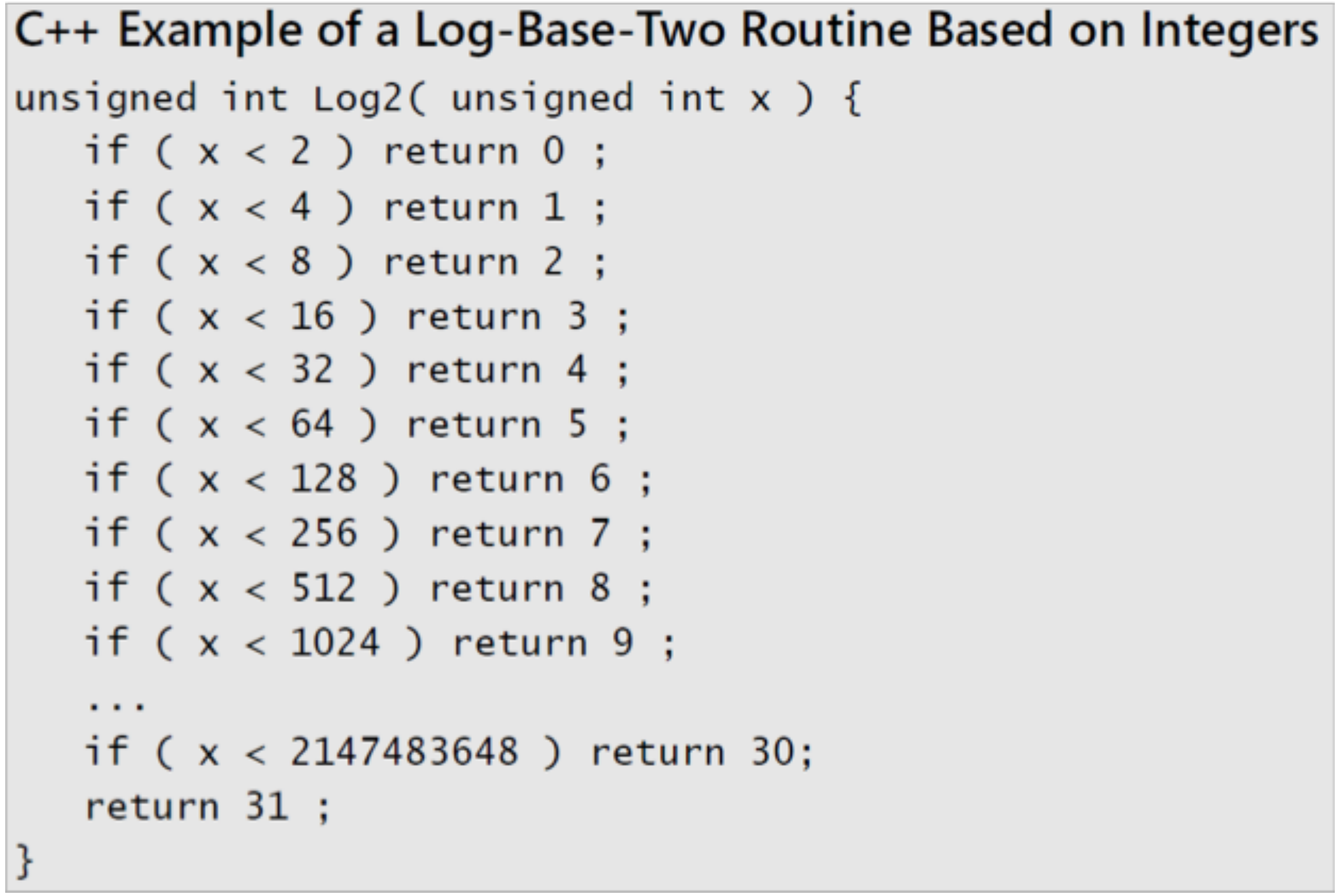
Language	Straight Time	Code-Tuned Time	Time Savings
C++	**9.66**	**5.97**	**38%**
Java	17.0	12.3	28%
PHP	2.45	1.50	39%

Expressions - Be Wary of System Routines

- System routines are expensive and provide accuracy that’s often wasted.
- Typical system math routines, <u>for example</u>, are designed to put an astronaut on the moon within ±2 feet of the target. If you don’t need that degree of accuracy, you don’t need to spend the time to compute it either.

Expressions - Be Wary of System Routines

- In the previous example, the *Log2()* routine returned an integer value but used a floating-point *log()* routine to compute it.
- That was problematic for an integer result, so write a series of integer tests that were perfectly accurate for calculating an integer log2.

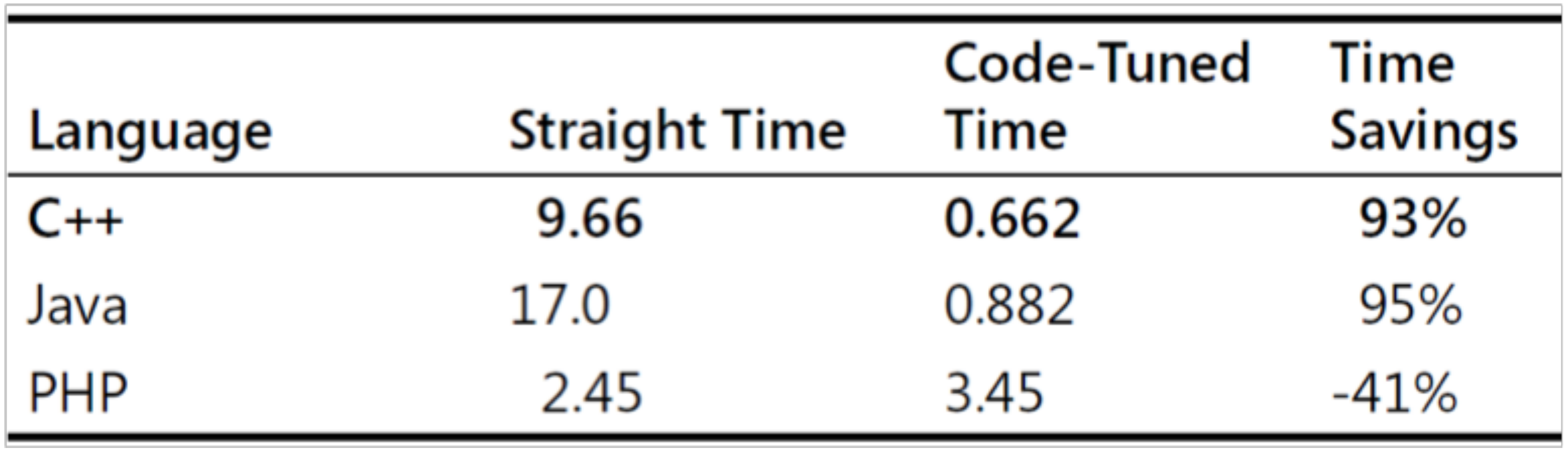


C++ Example of a Log-Base-Two Routine Based on Integers

```cpp
unsigned int Log2( unsigned int x ) {
   if ( x < 2 ) return 0 ;
   if ( x < 4 ) return 1 ;
   if ( x < 8 ) return 2 ;
   if ( x < 16 ) return 3 ;
   if ( x < 32 ) return 4 ;
   if ( x < 64 ) return 5 ;
   if ( x < 128 ) return 6 ;
   if ( x < 256 ) return 7 ;
   if ( x < 512 ) return 8 ;
   if ( x < 1024 ) return 9 ;
   ...
   if ( x < 2147483648 ) return 30;
   return 31 ;
}
```

Expressions - Be Wary of System Routines

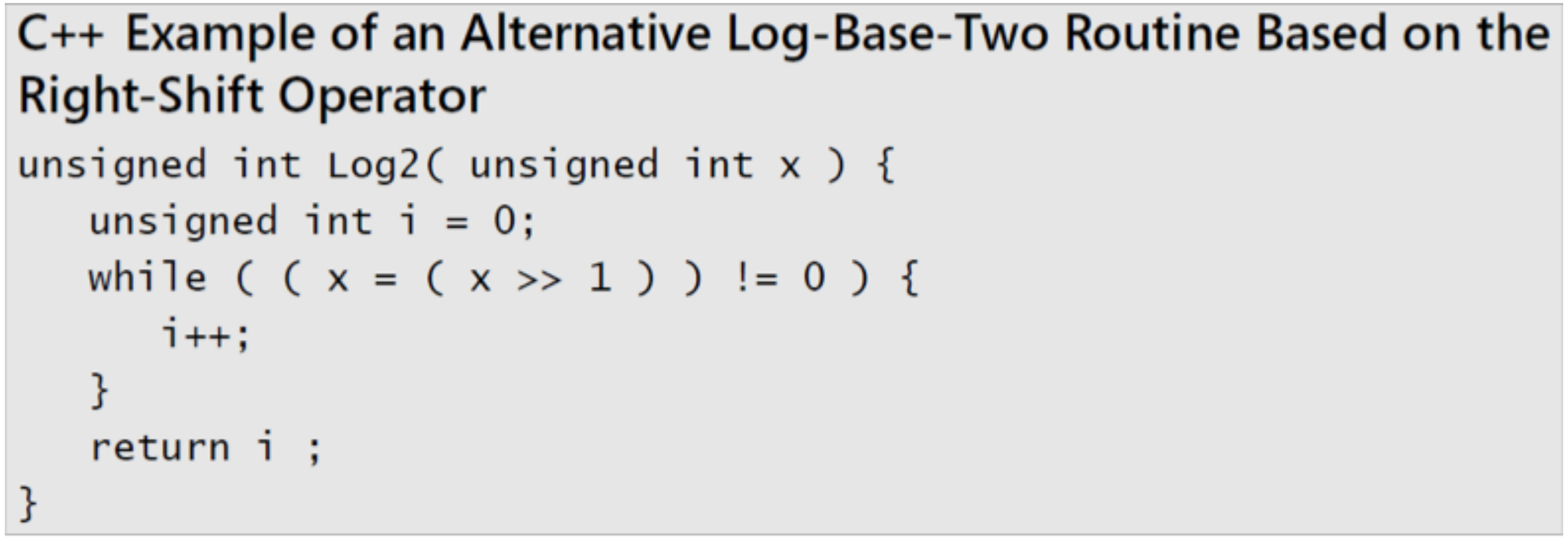
- This routine uses integer operations, never converts to floating point, and blows the doors off both floating-point versions:



Language	Straight Time	Code-Tuned Time	Time Savings
C++	**9.66**	**0.662**	**93%**
Java	17.0	0.882	95%
PHP	2.45	3.45	-41%

Expressions - Be Wary of System Routines

- Another option is to take advantage of the fact that a right-shift operation is the same as dividing by two.
- The number of times you can divide a number by two and still have a nonzero value is the same as the log2 of that number.



C++ Example of an Alternative Log-Base-Two Routine Based on the Right-Shift Operator

```
unsigned int Log2( unsigned int x ) {
   unsigned int i = 0;
   while ( ( x = ( x >> 1 ) ) != 0 ) {
      i++;
   }
   return i ;
}
```

Expressions - Be Wary of System Routines

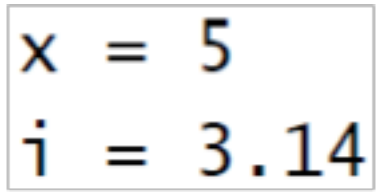
- To non-C++ programmers, this code is particularly hard to read. The complicated expression in the *while* condition is an example of a coding practice you should avoid unless you have a good reason to use it.
- This example highlights the value of not stopping after one successful optimization. The first optimization earned a respectable 30–40 percent savings but had nowhere near the impact of the second or third optimizations.

Expressions - Use the Correct Type of Constants

- Use named constants and literals that are the same type as the variables they're assigned to.
- *When a constant and its related variable are different types*, the compiler has to do a type conversion to assign the constant to the variable.
- A good compiler does the type conversion at **compile time** so that it *doesn't affect run*-time performance.

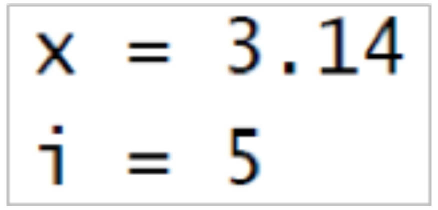
Expressions - Use the Correct Type of Constants

- A less advanced compiler or an interpreter generates code for a run-time conversion, so you might be stuck.
- Here are some differences in performance between the initializations of a floating-point variable *x* and an integer variable *i* in two cases. In the first case, the initializations look like this:



```
x = 5
i = 3.14
```

- and require type conversions, assuming *x* is a floating point variable and *i* is an integer. In the second case, they look like this:

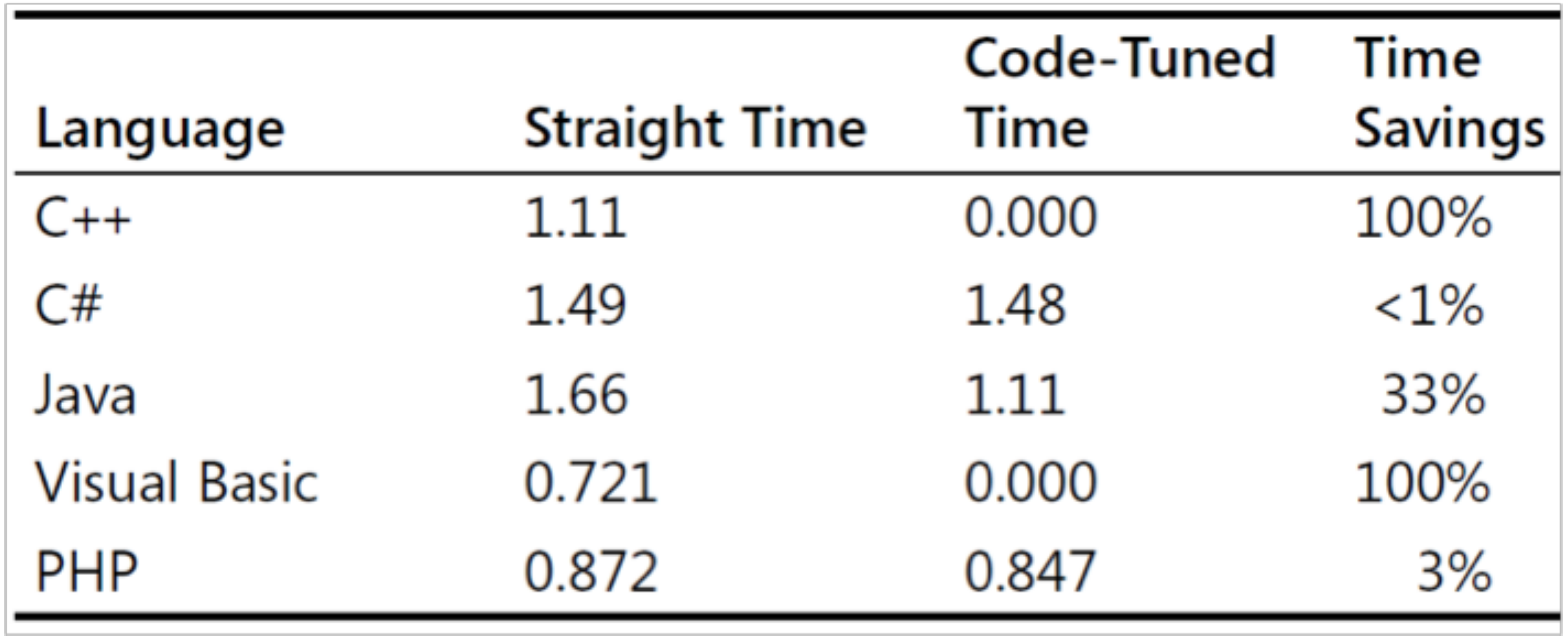


```
x = 3.14
i = 5
```

- and don't require type conversions.

Expressions - Use the Correct Type of Constants

- Performance gain



Language	Straight Time	Code-Tuned Time	Time Savings
C++	1.11	0.000	100%
C#	1.49	1.48	<1%
Java	1.66	1.11	33%
Visual Basic	0.721	0.000	100%
PHP	0.872	0.847	3%

Expressions - Precompute Results

- A common low-level design decision is the choice of whether to compute results on the fly or compute them once, save them, and look them up as needed.
- If the results are used many times, it’s often cheaper to compute them once and look them up the rest of the time.

Expressions - Precompute Results

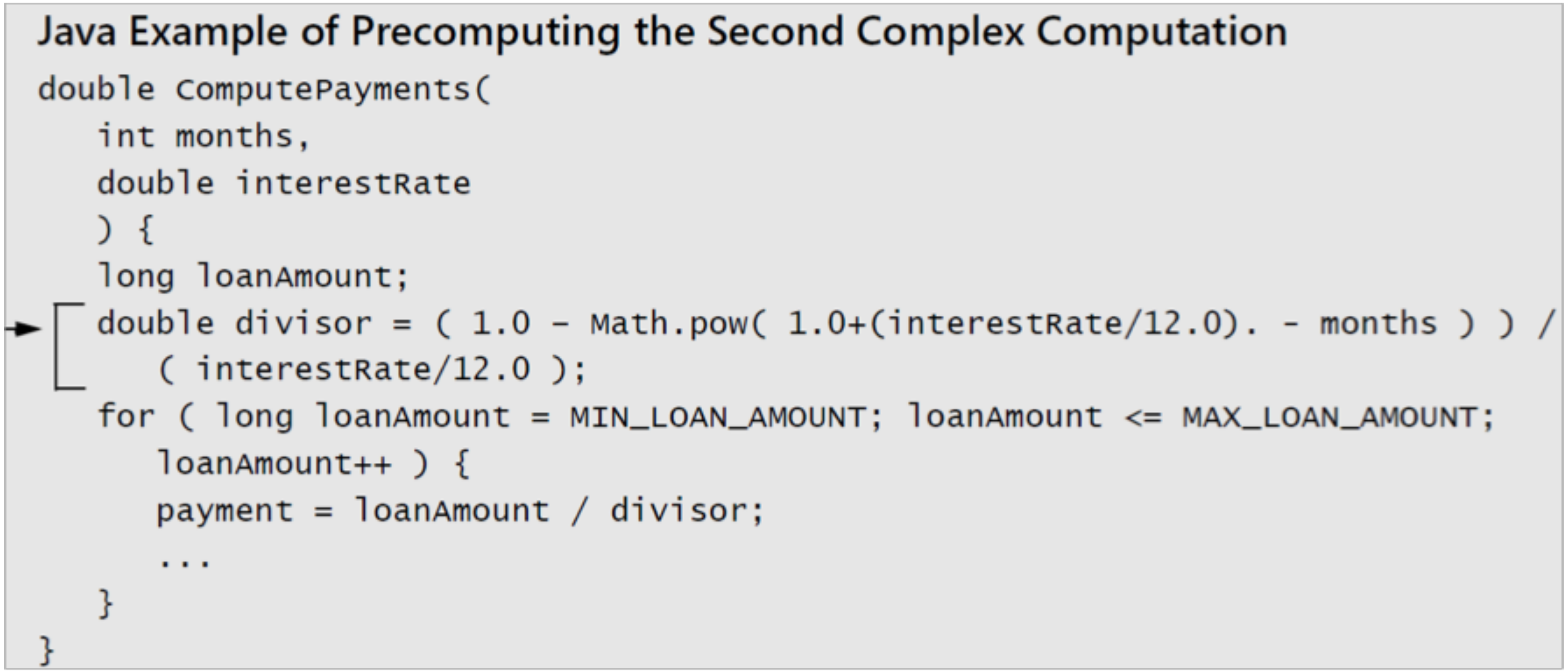
- At the simplest level, you might compute part of an expression outside a loop rather than inside.
- At a more complicated level, you might compute a **lookup table** once when program execution begins, using it every time thereafter, or you might store results in a data file or embed them in a program.

Expressions - Precompute Results

- **Any performance improvement suggestion?**

```
double ComputePayments(
   int months,
   double interestRate
   ) {
   for ( long loanAmount = MIN_LOAN_AMOUNT; loanAmount < MAX_LOAN_AMOUNT;
      loanAmount++ ) {
      payment = loanAmount / (
         ( 1.0 - Math.pow( 1.0+(interestRate/12.0), - months ) ) /
         ( interestRate/12.0 )
         );
      ...
   }
}
```

Expressions - Precompute Results

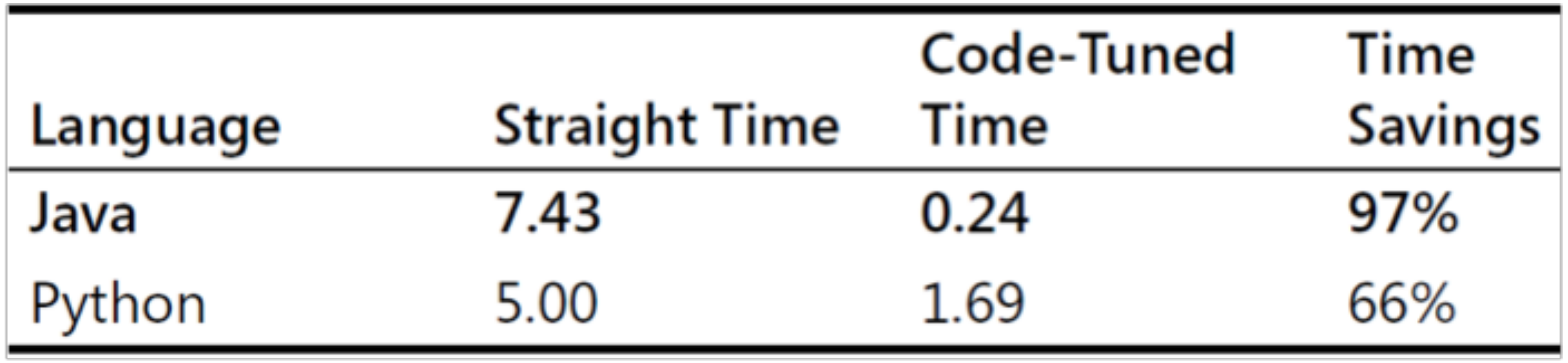


Java Example of Precomputing the Second Complex Computation

```java
double ComputePayments(
   int months,
   double interestRate
   ) {
   long loanAmount;
   double divisor = ( 1.0 - Math.pow( 1.0+(interestRate/12.0). - months ) ) /
      ( interestRate/12.0 );
   for ( long loanAmount = MIN_LOAN_AMOUNT; loanAmount <= MAX_LOAN_AMOUNT;
      loanAmount++ ) {
      payment = loanAmount / divisor;
      ...
   }
}
```

Expressions - Precompute Results

- This is similar to the techniques suggested earlier of putting array references and pointer dereferences outside a loop.
- The results for Java in this case are comparable to the results of using the precomputed table in the first optimization:



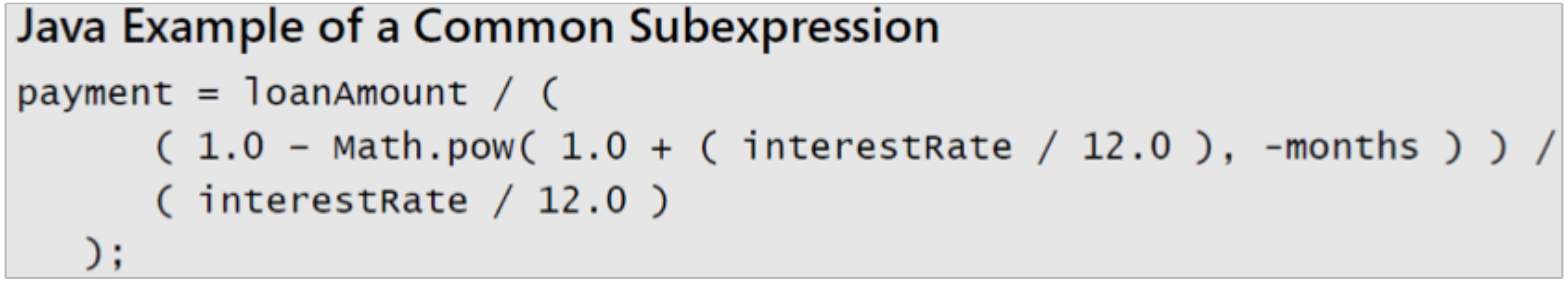
Language	Straight Time	Code-Tuned Time	Time Savings
Java	**7.43**	**0.24**	**97%**
Python	5.00	1.69	66%

Expressions - Precompute Results

- Optimizing a program by pre-computation can take several forms:
  - Computing results before the program executes, and wiring them into constants that are assigned at compile time
  - Computing results before the program executes, and hard-coding them into variables used at run time
  - Computing results before the program executes, and putting them into a file that's loaded at run time
  - Computing results once, at program startup, and then referencing them each time they're needed
  - Computing as much as possible before a loop begins, minimizing the work done inside the loop
  - Computing results the first time they're needed, and storing them so that you can retrieve them when they're needed again

Expressions - Eliminate Common Subexpressions

- If you find an expression that's repeated several times, assign it to a variable and refer to the variable rather than recomputing the expression in several places.
- The loan-calculation example has a common subexpression that you could eliminate. This is the original code:

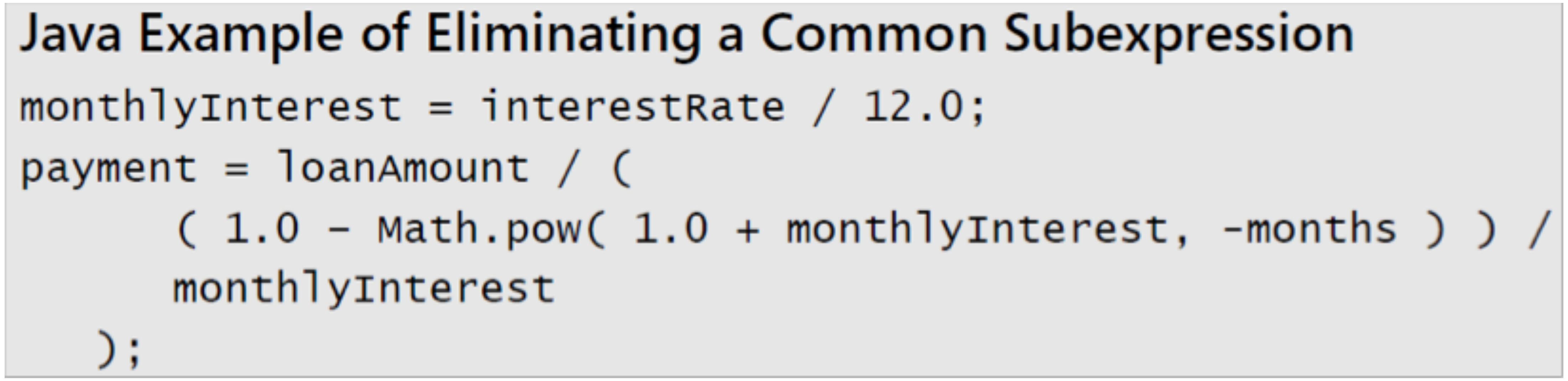


Java Example of a Common Subexpression

```java
payment = loanAmount / (
      ( 1.0 - Math.pow( 1.0 + ( interestRate / 12.0 ), -months ) ) /
      ( interestRate / 12.0 )
   );
```

Expressions - Eliminate Common Subexpressions

- You can assign *interestRate/12.0* to a variable that is then referenced twice rather than computing the expression twice.
- If you have chosen the variable name well, this optimization can *improve the code's readability at the same time that it improves performance*.

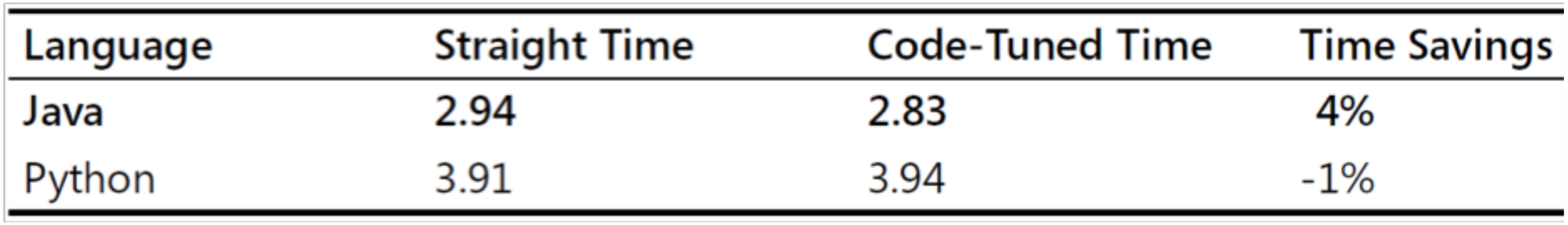


Java Example of Eliminating a Common Subexpression

```java
monthlyInterest = interestRate / 12.0;
payment = loanAmount / (
      ( 1.0 - Math.pow( 1.0 + monthlyInterest, -months ) ) /
      monthlyInterest
   );
```

Expressions - Eliminate Common Subexpressions

- The savings in this case don’t seem impressive:



Language	Straight Time	Code-Tuned Time	Time Savings
Java	**2.94**	**2.83**	**4%**
Python	3.91	3.94	-1%

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