The University Of Michigan

EECS402 Lecture 05

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Savitch Ch. 5
Arrays
Multi-Dimensional Arrays

Consider This Program

- Write a program to input 3 ints and output each value and their sum, formatted like a math problem

```
int i0, i1, i2;
int sum;

cout << "Enter int #1: ";
cin >> i0;
cout << "Enter int #2: ";
cin >> i1;
cout << "Enter int #3: ";
cin >> i2;

cout.setf(ios::right);
cout << "  " << setw(4) << i0 << endl;
cout << "+ " << setw(4) << i1 << endl;
cout << "+ " << setw(4) << i2 << endl;
cout << "  ----" << endl;

sum = i0 + i1 + i2;

cout << "  " << setw(4) << sum << endl;
```

```
Enter int #1: 54
Enter int #2: 102
Enter int #3: 7
    54
+  102
+    7
  ----
   163
```

Update To Program #1

- Your boss was so impressed, you are asked to update the program to work with 5 ints instead of 3

```
int i0, i1, i2, i3, i4;
int sum;

cout << "Enter int #1: ";
cin >> i0;
cout << "Enter int #2: ";
cin >> i1;
cout << "Enter int #3: ";
cin >> i2;
cout << "Enter int #4: ";
cin >> i3;
cout << "Enter int #5: ";
cin >> i4;

cout.setf(ios::right);
cout << "  " << setw(4) << i0 << endl;
cout << "+ " << setw(4) << i1 << endl;
cout << "+ " << setw(4) << i2 << endl;
cout << "+ " << setw(4) << i3 << endl;
cout << "+ " << setw(4) << i4 << endl;
cout << "  ----" << endl;

sum = i0 + i1 + i2 + i3 + i4;

cout << "  " << setw(4) << sum << endl;
```

```
Enter int #1: 50
Enter int #2: 30
Enter int #3: 108
Enter int #4: 1215
Enter int #5: 74
    50
+   30
+  108
+ 1215
+   74
  ----
  1477
```


Further Updates To Sum Program

- The previous programs worked fine and solved the problem that was presented
- Changing from 3 to 5 ints was easy – lots of copy/paste operations
- Now your boss asks for a program that works on 100 ints
  - Do you copy/paste 95 more inputs and outputs, update the variable names, and hope you did everything correctly?
- What if you are then requested to write one for 87 ints, and then 1000 ints, and then 743 ints, etc?

Intro To Arrays

- Array: A list of variables, *all of the same data type* that can be accessed via a common name
- The length of an array (the number of elements in the list) can be of any ***fixed*** length
- Syntax for declaring an array:
  - dataType arrayName[arrayLength];
    - dataType: Any available data type (int, float, user-defined types, etc)
    - arrayName: The name of the array (i.e. the common name used to access any variable in the list)
    - arrayLength: The number of elements that can be accessed via this array
- Example:
  - int quizGrades[10];
    - Declares an array of 10 integer elements, with the name "quizGrades"

More Info On Arrays

- Individual elements of the array are accessed by "indexing"
  - To index into an array, use the square brackets
  - In C/C++ array indices start at 0, and end at (length – 1)
  - Example: quizGrades[4] accesses the fifth element of the array
    - [0] would be the first, [1] the second, [2] the third, [3] the fourth, etc.
  - "quizGrades" is an array, but "quizGrades[4]" is an int, and can be used anywhere an int variable can be used
- If an int variable requires 4 bytes of memory, then the declaration:
  - int quizGrades[10];
  - sets aside 40 bytes (10 ints at 4 bytes each) of memory
  - Elements can be accessed using the following:
    - quizGrades[0], quizGrades[1], quizGrades[2], quizGrades[3], quizGrades[4], quizGrades[5], quizGrades[6], quizGrades[7], quizGrades[8], quizGrades[9]

A Quick Side Topic: Built-in Type Sizes

- Different kinds of data requires different amounts of memory to store it
  - We can store a character like 'T' or '+' in one byte
  - A large number such as 58,461,832 cannot possibly be represented in one byte though
  - If the amount of memory used for a piece of data depended on its *value*, the runtime environment would have a LOT more work to do
- All built-in datatypes are a fixed size.
  - Most commonly:
    - char: 1 byte (integer values -128 to +127)
    - int: 4 bytes (allows a range of ~4.2 billion (i.e. -2.1 billion to 2.1 billion))
    - float: 4 bytes
    - double: 8 bytes
    - bool: 1 byte

Arrays Stored In Memory

- Array elements are ***always*** stored in contiguous memory locations
  - This is what makes arrays so powerful!
  - Any individual element can be accessed very quickly
    - Knowledge of the element size and the memory address of the first element is all that is needed to determine the location of any element
    - ElementAddress = ArrayStartAddress + (Index * sizeOfArrayElement)

Assume that chars require 1 bytes of memory and ints require 4 bytes of memory.
The following declarations could result in the following layout of memory

```
char cAry[4];
int  iAry[4];
```

When you access cAry[2], address is computed:

```
1000 + 2 * 1 = 1002
```

When you access iAry[3], address is computed:

```
1004 + 3 * 4 = 1016
```

StartAddress, Index, ElemSize, ElemAddress

1000	cAry[0]	1012	iAry[2]
1001	cAry[1]	1013	
1002	cAry[2]	1014	
1003	cAry[3]	1015	
1004	iAry[0]	1016	iAry[3]
1005		1017	
1006		1018	
1007		1019	
1008	iAry[1]	1020	
1009		1021	
1010		1022	
1011		1023	

Using An Array For The Sum Program

- The sum program can be rewritten using a single array

```
int i;
int valsToSum[3];
int sum = 0;
for (i = 0; i < 3; i++)
{
  cout << "Enter int #" << i + 1 << ": ";
  cin >> valsToSum[i];
}

cout << valsToSum[0];
for (i = 1; i < 3; i++)
{
  cout << " + " << valsToSum[i];
}
cout << " = ";
for (i = 0; i < 3; i++)
{
  sum += valsToSum[i];
}
cout << sum << endl;
```

```
Enter int #1: 45
Enter int #2: 109
Enter int #3: 13
45 + 109 + 13 = 167
```


Extending To Sum Five Ints

- No copy/paste is required this time, just a few minor changes

```
int i;
int valsToSum[5];
int sum = 0;
for (i = 0; i < 5; i++)
{
  cout << "Enter int #" << i + 1 << ": ";
  cin >> valsToSum[i];
}

cout << valsToSum[0];
for (i = 1; i < 5; i++)
{
  cout << " + " << valsToSum[i];
}
cout << " = ";
for (i = 0; i < 5; i++)
{
  sum += valsToSum[i];
}
cout << sum << endl;
```

```
Enter int #1: 4
Enter int #2: 14
Enter int #3: 20
Enter int #4: 7
Enter int #5: 1
4 + 14 + 20 + 7 + 1 = 46
```

Even Better Version Of Sum Program

- Using a named constant for the array size allows for even easier updates

```
const int ARRAY_LENGTH = 3;
int i;
int valsToSum[ARRAY_LENGTH];
int sum = 0;
for (i = 0; i < ARRAY_LENGTH; i++)
{
  cout << "Enter int #" << i + 1 << ": ";
  cin >> valsToSum[i];
}

cout << valsToSum[0];
for (i = 1; i < ARRAY_LENGTH; i++)
{
  cout << " + " << valsToSum[i];
}
cout << " = ";
for (i = 0; i < ARRAY_LENGTH; i++)
{
  sum += valsToSum[i];
}
cout << sum << endl;
```

```
Enter int #1: 86
Enter int #2: 42
Enter int #3: 13
86 + 42 + 13 = 141
```


Extending To Five, One More Time


```
const int ARRAY_LENGTH = 5;
int i;
int valsToSum[ARRAY_LENGTH];
int sum = 0;
for (i = 0; i < ARRAY_LENGTH; i++)
{
  cout << "Enter int #" << i + 1 << ": ";
  cin >> valsToSum[i];
}

cout << valsToSum[0];
for (i = 1; i < ARRAY_LENGTH; i++)
{
  cout << " + " << valsToSum[i];
}
cout << " = ";
for (i = 0; i < ARRAY_LENGTH; i++)
{
  sum += valsToSum[i];
}
cout << sum << endl;
```

One simple change needed to support *any* number of elements

```
Enter int #1: 32
Enter int #2: 14
Enter int #3: 75
Enter int #4: 10
Enter int #5: 6
32 + 14 + 75 + 10 + 6 = 137
```

Array Bounds

- C/C++ does not do any bounds checking for you
  - Assumption is that programmer knows what he/she is doing
  - Formula for computing element address is used, even if index value is out-of-bounds for the array
  - The following example does not give any compile-time warnings or errors, nor does it give any run-time errors!

```
int main()
{
  int i;
  int ary[4];
  int var=0;
  for (i = 1; i <= 4; i++)
  {
    cout << "Enter int #" << i << ": ";
    cin >> ary[i];
  }
  cout << "Var: " << var << endl;
  return 0;
}
```

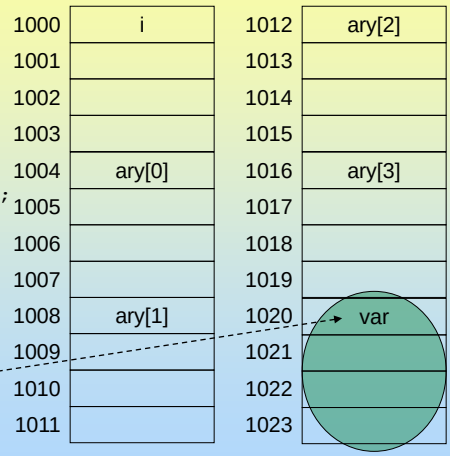
(Possible Results)

Enter int #1: 6
Enter int #2: 4
Enter int #3: 3
Enter int #4: 2
Var: 2

Explanation Of Previous Program

- Note: var was initialized to 0, was never changed in the program, but gets printed as 2 in the example output

```
int main()
{
  int i;
  int ary[4];
  int var=0;
  for (i = 1; i <= 4; i++)
  {
    cout << "Enter int #" << i << ": ";
    cin >> ary[i];
  }
  cout << "Var: " << var << endl;
  return 0;
}
```



When i == 4, ary[i] address is computed as:

1004 + 4 * 4 = 1020

StartAddress Index ElemSize ElemAddress

More On Array Bounds

- Why doesn't C/C++ do range checking for you?
  - Efficiency
    - Arrays are used a lot in programming
    - If every time an array was indexed, the computer had to do array bounds checking, things would be very slow
- In the previous example, programmer was only "off-by-one"
  - This is a very common bug in programs, and is not always as obvious as the previous example
  - In this case, the variable "var" was stored in that location and was modified
- What happens if the index is off far enough such that the memory address computed does not belong to the program?
  - Segmentation Fault

Segmentation Faults

- Segmentation faults (a.k.a. "seg faults") occur when your program tries to access a memory location that is does not have access to

```
int main()
{
  int ary[4];
  ary[0] = 10;
  cout << "Set ary[0]" << endl;
  ary[3] = 20;
  cout << "Set ary[3]" << endl;
  ary[9] = 30;
  cout << "Set ary[9]" << endl;
  ary[185] = 40;
  cout << "Set ary[185]" << endl;
  ary[600] = 50;
  cout << "Set ary[600]" << endl;
  ary[900] = 60;
  cout << "Set ary[900]" << endl;
  return 0;
}
```

(Possible Results)

Set ary[0]
Set ary[3]
Set ary[9]
Set ary[185]
Segmentation fault

Segmentation Faults, Cot'd

- A seg fault is considered to be a "crash" of the program
  - Program crashes are unacceptable and need to be prevented
- Just because the program didn't seg fault, does not mean there were no bounds problems
  - In the previous program, array was indexed using values 9 and 185, which are both out-of-bounds, without seg faulting

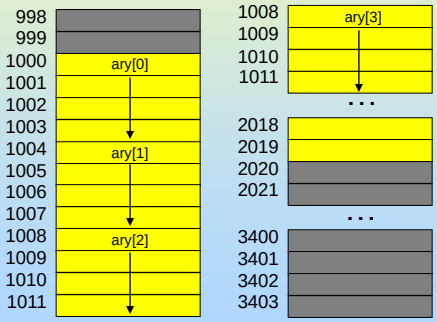
Memory address calculations

```
ary[9]:   1000 +   9 * 4 = 1036
ary[185]: 1000 + 185 * 4 = 1740
ary[600]: 1000 + 600 * 4 = 3400
```

Memory location belonging to your program

Memory location belonging to a different program

Seg fault occurs when trying to access memory that does not belong to your program



Initializing Array Values

- Array values can be initialized at the time they are declared
  - Assigned to comma-separated list of values enclosed in curly braces
  - If array length is unspecified, it is assumed to be exact size to fit initial values

```
int oddary[5] = {1, 3, 5, 7, 9}; //These two are
int oddary2[] = {1, 3, 5, 7, 9}; //equivalent..
```

  - If length is specified, but not enough initial values are provided, extra values are initialized to zero

```
int zeroAry[100] = {0};    //100 zeros!
int careful[100] = {100}; //100 followed by 99 zeros!
```

  - Use a loop to assign all elements to a specific value

```
int aryOf100s[100];        //uninitialized
for (i = 0; i < 100; i++)
{
  aryOf100s[i] = 100;      //elements assigned here to 100
}
```

Array Elements As Parameters

- Given the following array declaration:
  - int ary[5];
  - Indexing into the array results in an int
  - This int can be used anywhere an int can be used

```
void printInt(int val)
{
  cout << "Int is: " << val << endl;
}

int main()
{
  int iary[5] = {3, 5, 7, 9, 11};

  printInt(iary[3]);
  printInt(iary[4]);
  return 0;
}
```

Int is: 9
Int is: 11

Whole Arrays As Parameters

- Entire array can be passed into a function
- Example: Write a function that returns the sum of all values in an array
  - Specifying array length in parameter is optional, and usually not included

```
int sumAry(
     int num,  //# of elems in ary
     int ary[] //array of vals to sum
     )
{
  int sum = 0;
  int i;

  for (i = 0; i < num; i++)
  {
    sum += ary[i];
  }
  return sum;
}
```

```
int main()
{
  int iary[5]={3, 5, 7, 9, 11};
  int x;

  x = sumAry(5, iary);
  cout << "Sum: " << x << endl;

  return 0;
}
```

Sum: 35

Arrays Passed By Reference

- Arrays are passed by reference *by default*
  - No special syntax (i.e. no '&') is required to pass arrays by reference
- Why?
  - Pass-by-value implies a copy is made
  - If arrays were passed-by-value, every element of the entire array would have to be copied
    - For large arrays especially, this would be extremely slow
    - Also uses a lot of memory to duplicate the array
- Changing contents of an array inside a function changes the array as stored in the calling function as well!

Arrays Passed By Reference, Example


```
void sumArys(int num, int a[],
             int b[], int c[])
{
  int i;

  for (i = 0; i < num; i++)
  {
    c[i] = a[i] + b[i];
  }
}
```

```
int main()
{
  int i;
  int iary1[5] = {3, 5, 7, 9, 11};
  int iary2[5] = {2, 4, 6, 8, 10};
  int iary3[5]; //Uninitialized

  sumArys(5, iary1, iary2, iary3);

  for (i = 0; i < 5; i++)
  {
    cout << "iary3[" << i << "]: "
         << iary3[i] << endl;
  }

  return 0;
}
```

```
iary3[0]: 5
iary3[1]: 9
iary3[2]: 13
iary3[3]: 17
iary3[4]: 21
```

Changing "c" array in sumArys changes "iary3" in main, since arrays are passed by reference by default

Arrays As Parameters, Cot'd

- If you want to prevent array contents from changing in a function, use keyword "const"
  - Results in array being passed by "constant reference"
  - Array is still passed by reference – no inefficient copy is made
  - Keyword const prevents contents from being modified in the function
- Why bother?
  - To protect yourself from making mistakes
  - What would output of previous program be if sumArys was as follows:

```
void sumArys(int num, int a[],
             int b[], int c[])
{
  int i;
  for (i = 0; i < num; i++)
  {
    a[i] = b[i] + c[i];
  }
}
```

(Possible Results)

```
iary3[0]: 12
iary3[1]: -13377364
iary3[2]: -13392368
iary3[3]: 0
iary3[4]: 0
```


Updated sumArys

- Keyword const used for array parameters that won't change

Arrays "a" and "b" can not be changed within sumArys, only "c" can

```
void sumArys(
     int num,
     const int a[],
     const int b[],
     int c[]
     )
{
  int i;

  for (i = 0; i < num; i++)
  {
    c[i] = a[i] + b[i];
  }
}
```

This version provides a compile-time error, preventing problems resulting from this mistake

```
void sumArys(
     int num,
     const int a[],
     const int b[],
     int c[]
     )
{
  int i;

  for (i = 0; i < num; i++)
  {
    a[i] = b[i] + c[i];
  }
}
```

Using Variables As Array Sizes

- Array sizes must be specified as:
  - Named Constants: NUM_QUIZZES, TOTAL_STUDENTS, etc
  - Literal Values: 10, 62, etc
- Array sizes can ***not*** be variable!
- The following program *should not* compile, and will NOT be allowed in this course!

```
//This is an invalid program!!
int main()
{
  int num;

  cout << "Enter length of array: ";
  cin >> num;
  int iary[num]; //num is not constant!!!

  return 0;
}
```

Note: Adding the "-pedantic" flag to the g++ command line will ensure this is noticed
→ some g++ "extensions" that are often default ON will allow this unacceptable code to compile)
→ use "-pedantic" to make sure your code is standard compliant

```
prompt&% g++ -Wall -std=c++98 -pedantic -Werror arysize.cpp
arysize.cpp: In function 'int main()':
arysize.cpp:11:15: error: ISO C++ forbids variable length array 'iary' [-Werror=vla]
   int iary[num]; //num is not constant!!!
                 ^
cc1plus: all warnings being treated as errors
```


One Problem - What Is The Output?


```
int main(void)
{
  const int SIZE = 5;
  int i;
  int iary[SIZE] = {2,4,6,8,10};

  while (i < SIZE)
  {
    cout << iary[i] << endl;
    i++;
  }

  return 0;
}
```

Another Problem – What Is The Output?

```
int main(void)
{
  const int SIZE = 5;
  int i = 0;
  int iary[SIZE] = {2,4,6,8,10};

  while (i < SIZE)
  {
    cout << iary[i] << endl;
    iary[i]++;
  }

  return 0;
}
```


Two-Dimensional Arrays

- Arrays are not limited to one dimension
- A 2-D array is often called a matrix

Dimension 2 (columns)

Dimension 1 (rows)

	0	1	2	3	4	5
0	1	2	3	4	5	6
1	2	4	6	8	10	12
2	3	6	9	12	15	18
3	4	8	12	16	20	24
4	5	10	15	20	25	30
5	6	12	18	24	30	36

Declaring a 2-D Array

- Syntax for a 2-D array is similar to a 1-D
  - dataType arrayName[numRows][numCols];
- While there are 2 dimensions, each element must still be of the same data type
- To declare matrix shown on previous slide (6 rows, 6 columns)
  - int matrix[6][6];
- If ints are stored in 4 bytes, then the above declaration sets aside 6 * 6 *4 = 144 bytes of memory
- A 2-D array is really just a 1-D array, where each individual element is itself a 1-D array

Initializing a 2-D Array

- Initialization of 1-D array was a comma separated list of values enclosed in curly braces
- 2-D array initialization is an initialization of a 1-D array of 1-D arrays

1-D Array

```
int matrix[6][6] = {{ 1, 2, 3, 4, 5, 6},
                    { 2, 4, 6, 8,10,12},
                    { 3, 6, 9,12,15,18},
                    { 4, 8,12,16,20,24},
                    { 5,10,15,20,25,30},
                    { 6,12,18,24,30,36}};
```

Assigning 2-D Array Elements

- Individual elements can be assigned using two sets of brackets
  - The following code creates a matrix with the same values as shown earlier, but uses a mathematical formula instead of initialization

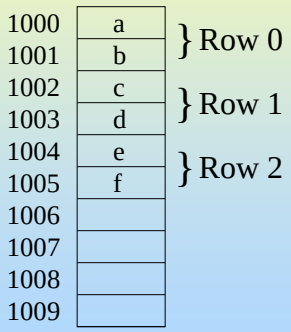
```
int matrix[6][6];

for (i = 0; i < 6; i++)
{
  for (j = 0; j < 6; j++)
  {
    matrix[i][j] = (i + 1) * (j + 1);
  }
}
```


2-D Arrays In Memory

- As with ***all*** arrays, 2-D arrays are stored contiguously in memory
- Computer memory is inherently 1-dimensional though
  - Row 2's elements are stored immediately following the last element from row 1

```
char cary[3][2] = {{'a','b'},{'c','d'},{'e','f'}};
```



2-D Array Memory Address Determination

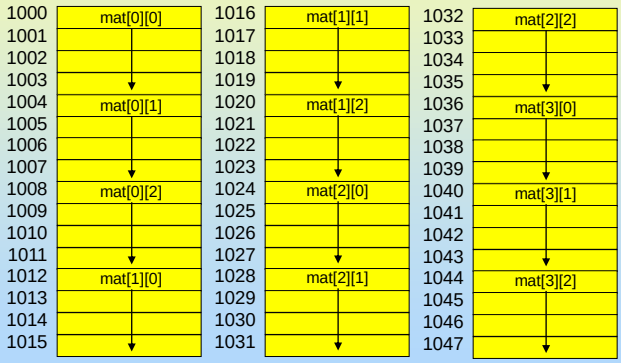
- As with 1-D arrays, any element's address can be computed very quickly
  - Knowledge of array starting address, size of each element, ***and the number of columns in each row*** is required

```
int mat[4][3];
```

mat[1][2]
1000 + (3 * 1) * 4 + 2 * 4 = 1020

mat[3][1]
1000 + (3 * 3) * 4 + 1 * 4 = 1040

StartAddr
#Columns
RowIndex
ElementSize
ColumnIndex
ElementSize
ElementAddr



Single 2-D Array Elements

- Use single element anywhere variable of that type can be used

```
void printInt(int i)
{
  cout << "Int is: "  << i << endl;
}

int main()
{
  int matrix[3][2] = {{2,4},{6,8},{10,12}};

  printInt(matrix[1][0]);
  printInt(matrix[2][1]);

  return 0;
}
```

Int is: 6
Int is: 12

Using Rows Of 2-D Arrays

- Since a 2-D array is a 1-D array of 1-Darrays, each row can be used a 1-D array

```
int sumAry(
     int num,  //# of elems in ary
     const int ary[] //array of vals
                     //to sum
     )
{
  int sum = 0;
  int i;

  for (i = 0; i < num; i++)
  {
    sum += ary[i];
  }

  return sum;
}
```

```
int main()
{
  int matr[3][5]={{3, 5, 7, 9, 11},
                  {2, 4, 6, 8, 10},
                  {1, 2, 3, 4,  5}};
  int x;

  x = sumAry(5, matr[0]);
  cout << "Row1 Sum: " << x << endl;
  x = sumAry(5, matr[1]);
  cout << "Row2 Sum: " << x << endl;

  return 0;
}
```

```
Row1 Sum: 35
Row2 Sum: 30
```


Whole 2-D Arrays As Parameters

- When passing a 2-D array as a parameter, function must know the number of columns
  - Recall this is required in order to compute address of an element
  - First dimension can be left unspecified, second dimension ***can not!***

```
void printAry(int rows,
              const char ary[][2])
{
  int i;
  int j;
  for (i = 0; i < rows; i++)
  {
    for (j = 0; j < 2; j++)
    {
      cout << ary[i][j] << " ";
    }
    cout << endl;
  }
}
```

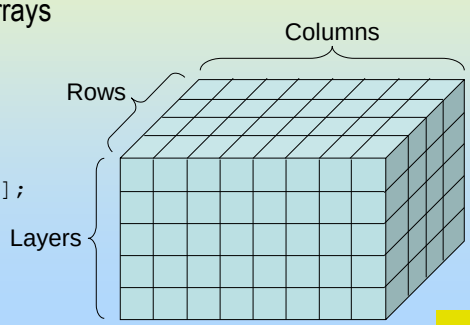
```
int main()
{
  char matrix[3][2] =
                {{'a','b'},
                 {'c','d'},
                 {'e','f'}};
  printAry(3, matrix);
  return 0;
}
```

```
a b
c d
e f
```

Three-Dimensional Arrays

- C++ arrays can have as many dimensions as necessary
- 1-D Array: List of values
- 2-D Array: Matrix of values, consisting of rows and columns
- 3-D Array: Cube of values, consisting of rows, columns, and layers
  - In other words, a 3-D array is a 1-D array of matrices
  - In other words, a 3-D array is a 1-D array, where each element is a 1-D array whose elements are 1-D arrays
  - Got that?

```
const int LAYERS = 5;
const int ROWS = 4;
const int COLS = 8;
int threeDAry[LAYERS][ROWS][COLS];
```



A Quick 3D Array Example


```
void printAry(
      int num,
      const char ary[][4])
{
  int i;
  int j;
  for (i = 0; i < num; i++)
  {
    for (j = 0; j < 4; j++)
    {
      cout << ary[i][j] << " ";
    }
    cout << endl;
  }
}
```

```
int main(void)
{
  char cary [2][3][4] =
     { { {'a','b','c','d'},
         {'e','f','g','h'},
         {'i','j','k','l'} },
       { {'m','n','o','p'},
         {'q','r','s','t'},
         {'u','v','w','x'} } };
  cout << "cary [0]: " << endl;
  printAry(3, cary [0]);
  cout << "cary [1]: " << endl;
  printAry(3, cary [1]);

  return 0;
}
```

```
cary [0]:
a b c d
e f g h
i j k l
cary [1]:
m n o p
q r s t
u v w x
```