Array Concepts

Array Declarations (1)

Fortran 90 uses the DIMENSION attribute to declare arrays. The most common examples are:

```
INTEGER, DIMENSION(30) :: days_in_month
CHARACTER(LEN=10), DIMENSION(250) :: names
REAL, DIMENSION(350,350) :: box_locations
```

In Fortran the starting index defaults to a value of 1 (not 0 as is common in many other languages - C/C++/Python)

Array Declarations (2)

BUT you can specify a lower bound different than 1. It will just default to 1 if you omit it.

The syntax is <lower bound>:<upper bound> where the bound values are INTEGERs.

```
INTEGER, DIMENSION(0:99) :: arr1, arr2, arr3
CHARACTER(LEN=10), DIMENSION(1:250) :: names
REAL, DIMENSION(-10:10,-10:10) :: pos1, pos2
REAL, DIMENSION(0:5,1:7,2:9,1:4,-5:-2) :: pos1, pos2
```

Alternative Form

The same base type but different bounds:

```
INTEGER :: arr1(0:99), arr2(0:99), days_in_month(1:12)
REAL :: box_locations(1:350), pos1(-10:10,-10:10)
```

Don't mix the two forms!

Array Terminology

REAL :: A(0:99), B(3,6:9,5)

- The rank of an array is the number of dimensions.

  The maximum number of dimensions is 7!

  A has rank 1 and B has rank 3

- The bounds are the upper and lower limits.

  A has bounds 0:99 and B has bounds 1:3, 6:9 and 1:5

- The extent of an array dimension is the range of its index or indices. (upperbound-lowerbound+1)

```
REAL :: A(0:99), B(3,6:9:5)
```

- The size of an array is the total number of elements.

  A has size 100 and B has size 60

- The shape of an array is its rank and extents.

  A has shape (100) and B has shape (3,4,5)

  Arrays are **conformable** if they share the same shape. The bounds do not have to be the same.

Array References

In general, there are **three** different ways to reference arrays:

- individual array elements arr1(5), myintval(-10)
- entire array arr1 or arr1(:)
- array section arr1(5:24), arr1(-10:-7)

Array Element References

An array index can be any integer expression
e.g., months(j) selects the jth month

```
INTEGER, DIMENSION(-50:50) :: val
DO i = -50,50
   val(i) = 2*i
END DO
```

Sets val to -100, -98, ..., 98, 100

Index Expressions

Set the even elements to the odd indices and vice versa

```
INTEGER, DIMENSION(1:80) :: series
DO K = 1,40
   series(2*K) = 2*K-1
   series(2*K-1) = 2*K
END DO
```

You can go completely overboard, too

```
series(int(1.0+80.0*cos(123.456))) = 42
```

Example of Arrays: Sorting

Sort a list of numbers into ascending order
The top level algorithm is:

1. Read the numbers and store them in an array.
2. Sort them into ascending order of magnitude.
3. Print them out in sorted order.

Selection Sort

This is NOT how to write a general sort

It takes $O(N^2)$ time compared to $O(N \log(N))$

For each location J from 1 to N-1

    For each location K from J+1 to N

        If the value at J exceeds that at K

            Then swap them

    End of loop

End of loop

Let's take a look: sort10.f90

Using Arrays as Objects

Set all the elements of an array to a single value

```
INTEGER, DIMENSION(1:50) :: series
series = 0
```

You can use entire arrays as simple variables provided they are conformable

```
REAL, DIMENSION(200) :: arr1, arr2
arr1 = arr2 + 1.23*exp(arr1/4.56)
```

The RHS and any LHS indices are evaluated, and then the RHS is assigned to the LHS.

Array Sections

Array sections create an aliased subarray
It is a simple variable with a value

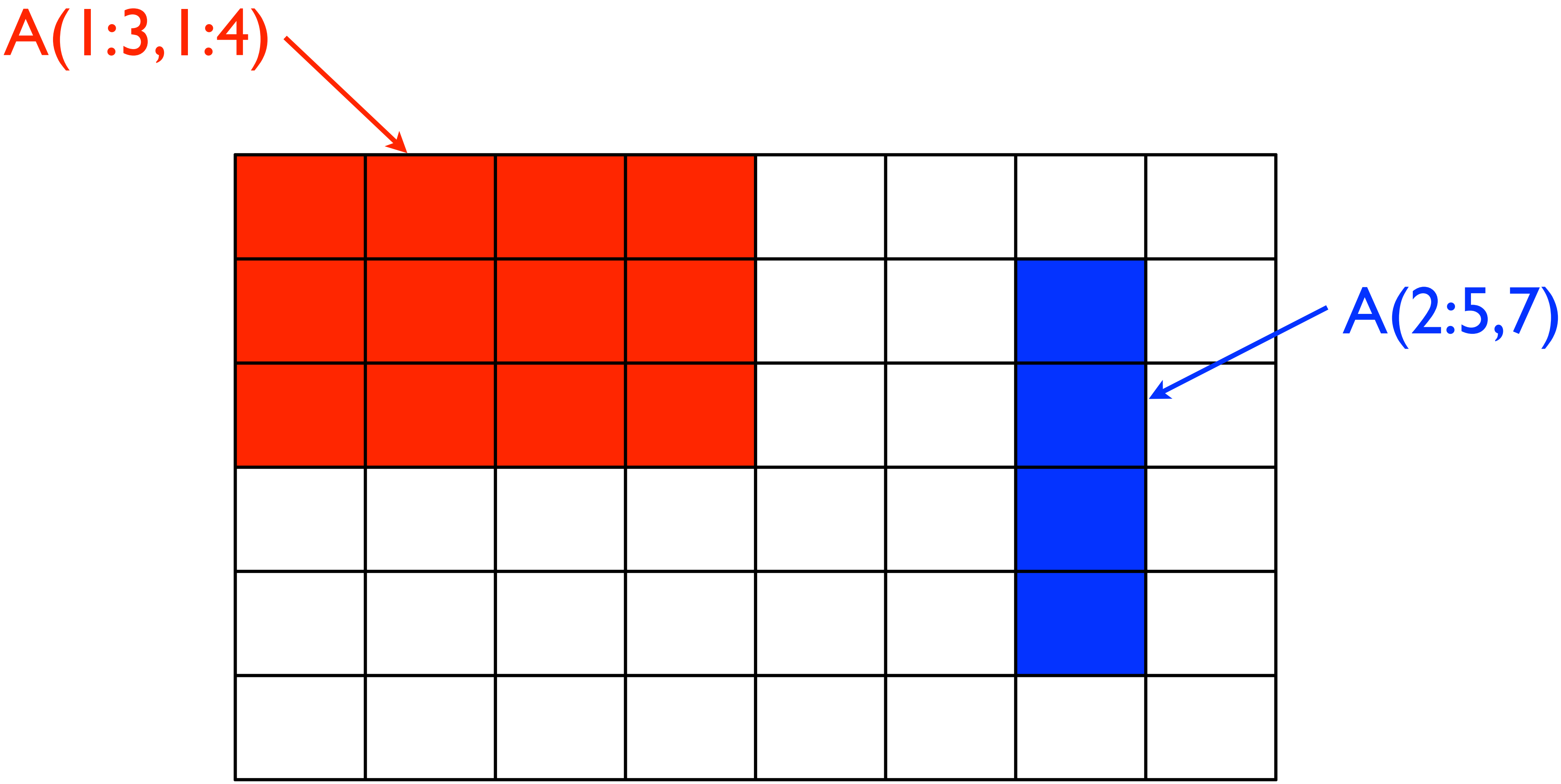
```
INTEGER :: arr1(100), arr2(50),arr3(100)
arr1(1:63) = 5;  arr1(64:100) = 7
arr2 = arr1(1:50)+arr3(51:100)
```

Even this is legal but it forces a copy:

```
arr1(26:75) = arr1(1:50)+arr1(51:100)
```

Array Sections

A(1:6, 1:8)



Short Form

Existing array bounds may be omitted
Especially useful for multidimensional arrays

If we have REAL, DIMENSION(1:6, 1:8) :: A

A(3:, :4) is the same as A(3:6, 1:4)
A, A(:,:) and A(1:6, 1:8)

A(6, :) is the 6th row as a 1-D vector
A(:, 3) is the 3rd column as a 1-D vector
A(6:6, :) is the 6th row as a 1x8 matrix
A(:, 3:3) is the 3rd columns as a 6x1 matrix

Conformability of Sections

The conformability rule applies to sections, too.

```
REAL :: A(1:6, 1:8), B(0:3, -5:5), C(0:10)

A(2:5,1:7) = B(:,-3:3)          ! both have shape (4,7)
A(4,2:5) = B(:,0) + C(7:)       ! all have shape (4)
C(:) = B(2,:)                   ! both have shape (11)
```

But these would be illegal

```
A(1:5,1:7) = B(:,-3:3)   ! shapes (5,7) and (4,7)
A(1:1,1:3) = B(1,1:3)    ! shapes (1,3) and (3)
```

Sections with Strides

Array sections need not be contiguous
Any uniform progression is allowed

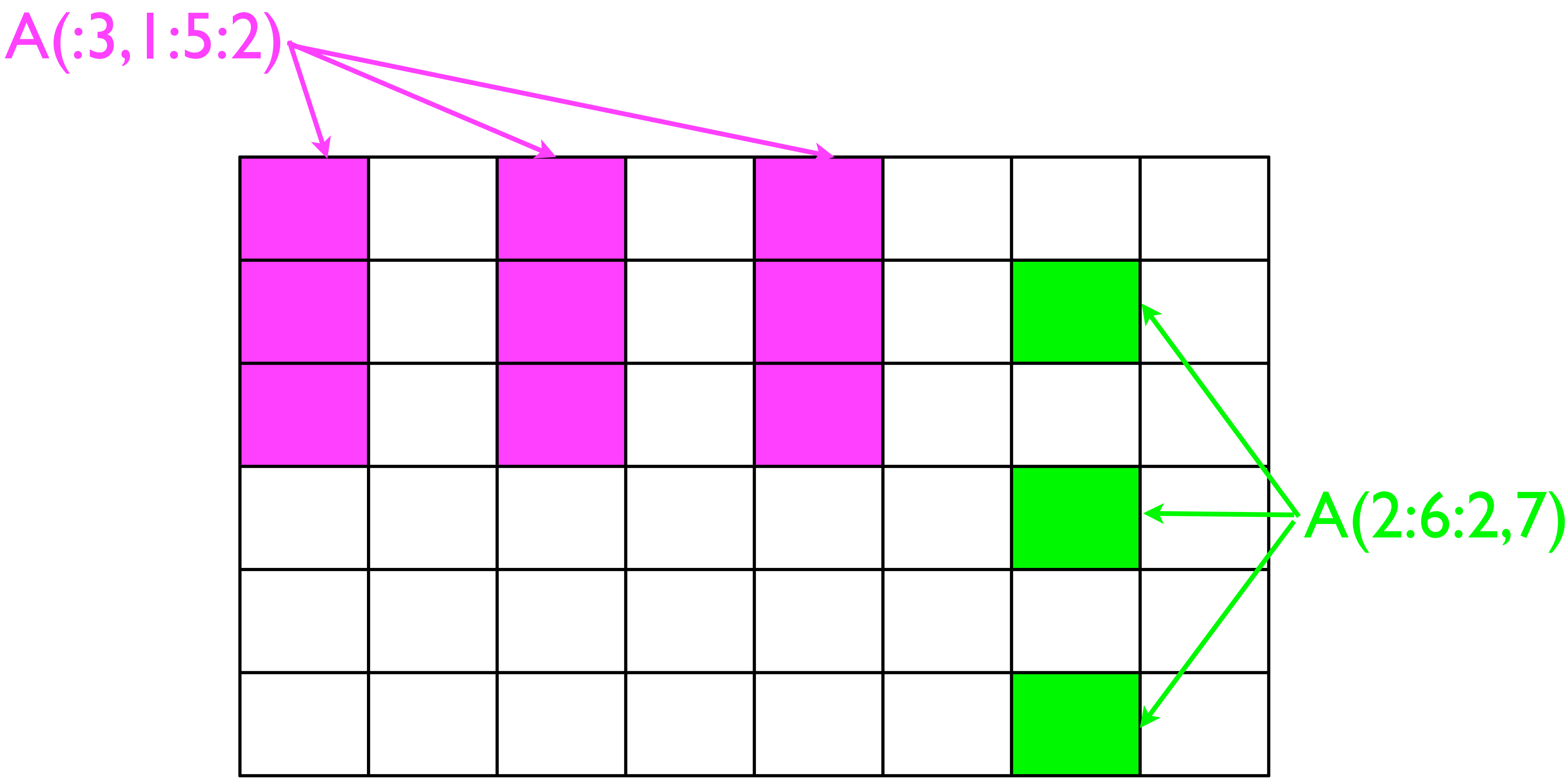
This is exactly like a more compact DO-loop
Negative strides are allowed, too

```
INTEGER :: arr1(1:100), arr2(1:50), arr3(1:50)
arr1(1:100:2) = arr2     ! Sets every odd element
arr1(100:1:-2) = arr3    ! Even elements, reversed

arr1 = arr1(100:1:-1)   ! Reverses the order of arr1
```

Strided Sections

A(1:6, 1:8)



Array Bounds

Subscripts and sections must be within the array bounds
The following are invalid (undefined behavior)

```
REAL :: A(1:6, 1:8), B(0:3, -5:5), C(0:10)

A(2:5,1:7) = B(:,-6:3)
A(7,2:5) = B(:,0)
C(:11) = B(2,:)
```

Most compilers will NOT check for this automatically!

Errors will lead to overwriting, etc. and CHAOS

Elemental Operations

Most built-in operators/functions are elemental
They act element-by-element on arrays

```
REAL, DIMENSION(1:200) ::  arr1, arr2, arr3
arr1 = arr2 + 1.23*EXP(arr3/4.56)
```

Comparisons and logical operations, too

```
REAL, DIMENSION(1:200) ::  arr1, arr2, arr3
LOGICAL, DIMENSION(1:200) :: flags
flags = (arr1 > EXP(arr2) .OR.  + arr3 < 0.0)
```

Array Intrinsic Functions (1)

There are over 20 useful intrinsic procedures
They can save a lot of coding and debugging

```
SIZE(x [,n])     ! The size of x (an integer scalar)
SHAPE(x)         ! The shape of x (an integer vector)

LBOUND(x [,n])   ! The lower bound of x
UBOUND(x [,n])   ! The upper bound of x
```

If n is present then compute for that dimension only
And the result is an integer scalar
Otherwise the result is an integer vector

Array Intrinsic Functions (2)

MINVAL(x) ! The minimum of all elements of x
MAXVAL(x) ! The maximum of all elements of x

These return a scalar of the same type as x

MINLOC(x) ! The indices of the minimum
MAXLOC(x) ! The indices of the maximum

These return an integer vector, just like SHAPE

Array Intrinsic Functions (3)

```
SUM(x [,n])            ! The sum of all elements of x
PRODUCT(x [,n])        ! The product of all elements of x
```

If n is present the compute for that dimension only

TRANSPOSE(x) means $X_{ij} \Rightarrow X_{ji}$

It must have two dimensions but need not be square

DOT_PRODUCT(x,y) means $\sum_i X_i \cdot Y_i \Rightarrow Z$

Two vectors, both of same length and type

Array Intrinsic Functions (4)

MATMUL(x,y) means $\sum_k X_{ik} \cdot Y_{kj} \Rightarrow Z_{ij}$

- 2nd dimension of X must match the 1st of Y
- The matrices need not be the same shape
- Either X or Y may be a vector

Many more for array reshaping and array masking

Array Element Order (1)

This is also called the "storage order"

Traditional term is "column-major order"
But Fortran arrays are not laid out in columns!
Much clearer: "first index varies fastest"

```
REAL, DIMENSION(1:3,1:4) :: A
```

The elements of A are stored in this order:

```
A(1,1),A(2,1),A(3,1),A(1,2),A(2,2),A(3,2),
A(1,3),A(2,3),A(3,3),A(1,4),A(2,4),A(3,4)
```

Array Element Order (2)

Opposite to C, Matlab, Mathematica, IDL, etc.

You don't often need to know the storage order
Three important cases where you do:

- I/O of arrays, especially unformatted
- Array constructors and array constants
- Optimization (caching and locality)

Simple Array I/O (1)

Arrays and sections can be included in I/O
These are expanded in array element order

```
REAL, DIMENSION(3,2) :: oxo
READ *, oxo
```

This is exactly equivalent to:

```
READ *, oxo(1,1), oxo(2,1), oxo(3,1), &
    oxo(1,2), oxo(2,2), oxo(3,2)
```

Simple Array I/O (2)

Array sections can also be used

```
REAL, DIMENSION(100) :: nums
READ *, nums(30:50)

REAL, DIMENSION(3,3) :: oxo
READ *, oxo(:3), oxo(3:1:-1,1)
```

This last statement equivalent to:

```
READ *, oxo(1,3), oxo(2,3), oxo(3,3), &
        oxo(3,1), oxo(2,1), oxo(1,1)
```

Array Constructors (1)

Commonly used for assigning array values

An array constructor will create a temporary array

```
INTEGER, DIMENSION(6) :: marks
marks = (/ 10, 25, 32, 54, 56, 60 /)
```

Constructs an array with the elements

10, 25, 32, 54, 56, 60

And then copies that array into marks

Fortran 2003 addition: Also can use square brackets

```
marks = [ 10, 25, 32, 54, 56, 60 ]
```

Array Constructors (2)

Variable expressions are okay in constructors

```
marks = (/ x, 2.0*y, SIN(t*w/3.0), ... /)
```

They can be used anywhere an array can be
Except where you might assign to them!

All expressions must be the same type
This can be relaxed in Fortran 2003

Array Constructors (3)

Arrays can be used in the value list
They are flattened into array element order

Implied DO-loops (as in I/O) allow sequences

If n has the value 5:

```
marks = (/ 0.0, (k/10.0,k=2,n), 1.0 /)
```

This is equivalent to:

```
marks = (/ 0.0, 0.2, 0.3, 0.4, 0.5, 1.0 /)
```

Constants and Initialization (1)

Array constructors can be very useful for this
All elements must be initialization expressions
i.e., ones that can be evaluated at compile time

For rank one arrays just use a constructor

```
REAL, PARAMETER :: a(3) = (/ 1.23, 4.56, 7.89 /)
```

```
REAL :: b(3) = (/ 1.23, 4.56, 7.89 /)
b = exp(b)
```

Constants and Initialization (2)

Other types can be initialized in the same way

```
CHARACTER(LEN=4), DIMENSION(5) :: &
  names = (/ 'Fred', 'Joe', 'Bill', 'Bert', 'Alf' /)
```

Initialization expressions are allowed

```
INTEGER, PARAMETER :: N = 3, M = 6, P = 12
INTEGER :: arr(3) = (/ N, (M/N), (P/N) /)
```

Constants and Initialization (3)

What about this?

```
REAL :: arr(3) = (/ 1.0, exp(1.0), exp(2.0) /)
```

Fortran 90 does NOT allow this but Fortran 2003 does

Not just intrinsic functions but all sorts of things

Multiple Dimensions

Constructors cannot be nested - e.g., NOT:

```
REAL, DIMENSION(3,4) :: xvals =  &
(/ (/ 1.1, 2.1, 3.1 /), (/ 1.2, 2.2, 3.2 /), &
   (/ 1.3, 2.3, 3.3 /), (/ 1.4, 2.4, 3.4 /) /)
```

They construct only rank one arrays

Use the RESHAPE intrinsic function to construct higher rank arrays.

Allocatable Arrays (1)

Arrays can be declared with an unknown shape
Use the ALLOCATABLE attribute in the type declaration

```
INTEGER, DIMENSION(:), ALLOCATABLE :: counts
REAL, DIMENSION(:,:,:), ALLOCATABLE :: values
```

They become defined when space is allocated

```
ALLOCATE(counts(1:1000000))
ALLOCATE(value(0:N,-5:5,M:2*N+1))
```

You can also allocate multiple arrays in a single ALLOCATE statement

Allocatable Arrays (2)

Failures will terminate the program
You can trap most allocation failures

```
INTEGER :: istat
ALLOCATE(arr(0:100,-5:5,7:14),STAT=istat)
IF (istat /= 0) THEN
   ...
ENDIF
```

Arrays can be deallocated using

```
DEALLOCATE(counts)
```

Example

```
INTEGER, DIMENSION(:), ALLOCATABLE :: counts
INTEGER :: size, code
!-- Ask the user how many counts he has
PRINT *, 'Type in the number of counts'
READ *, size
!-- Allocate memory for the array
ALLOCATE(counts(1:size),STAT=code)
IF (code /= 0.0) THEN
      PRINT *, 'Error in allocate statement'
      ...
ENDIF
```

WHERE Construct (1)

Used for masked array assignment

Example: Set all negative elements of an array to zero

```
REAL, DIMENSION(20,30) :: array

DO j = 1,30
  DO k = 1,20
    IF (array(i,j) < 0.0) array(k,j) = 0.0
  ENDDO
ENDDO
```

But the WHERE statement is much more convenient

```
WHERE (array < 0.0) array = 0.0
```

WHERE Construct (2)

It has a statement construct form, too

Example: Set all negative elements of an array to zero

```
WHERE (array < 0.0)
   array = 0.0
ELSE WHERE
   array = 0.01 * array
ENDWHERE
```

Masking expressions are LOGICAL arrays

You can use an actual array there, if you want

Masks and assignments need the same shape