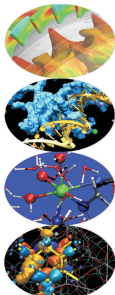


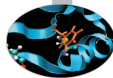
Introduction to modern Fortran

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CINECA Bologna - SCAI Department

Bologna, 17-20 October 2016





Part I

A Fortran Survey 1

Program main unit, source formats, comments, declarations and instructions. Fundamental operators, expressions, conditional constructs, loops, functions: arguments passing, intent, interface, intrinsic and external functions. Modules: contains and use. Intrinsic types: integer, real, complex, logical, and parameter. I/O base.



Introduction

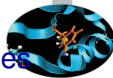
Fortran Basics

More Fortran Basics

Integer Types and Iterating

More on Compiling and Linking

Homeworks



- ▶ Developed in the 50s among the earliest high level languages (HLL)
- ▶ Widely and rapidly adopted in the area of numerical, scientific, engineering and technical applications
- ▶ First standard in 1966: Fortran 66
 - ▶ The first of all programming language standards
- ▶ Second standard in 1978: Fortran 77
- ▶ Third standard in 1991: Fortran 90
 - ▶ Adds new, modern features such as structured constructs, array syntax and ADT
 - ▶ Extended and revised in 1997: Fortran 95
 - ▶ Further extended with published Technical Reports
- ▶ Fourth standard in 2004: Fortran 2003
 - ▶ Major revision, incorporates TRs, adds many new features (OO!), still not fully supported
- ▶ Fifth standard in 2010: Fortran 2008



- ▶ Strongly oriented to *number crunching*
- ▶ Efficient language, highly optimized code
 - ▶ Basic data types and operators mapping "naturally" to CPUs
 - ▶ Translated by a compiler to machine language
 - ▶ Language rules allow for aggressive, automatic optimization
 - ▶ Facilities to build new data types from the basic ones
 - ▶ Flexible flow control structures mapping the most common numerical computing use cases
- ▶ Scientific computing specialized syntax
 - ▶ A wealth of math data types and functions available as intrinsics of the language
 - ▶ Compact, readable array syntax to operate on many values as a whole



► Why Fortran is bad

- Current standard embodies four different language versions,...
- ... all of them still alive in legacy codes
- Non-numeric computing in Fortran is a real pain
- There are more C than Fortran programmers
- GUI and DB accesses are best programmed in C
- C99 partly addressed numerical computing needs



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► Why Fortran is good

- Fortran is highly tuned for numerical computation
- Fortran is older and more “rigid” than C, compilers optimize better
- Much better than C at managing user defined data types
- Object-oriented features are now part of the language
- Provides facilities for interoperability with C and other languages



- ▶ Teach you the fundamentals of modern Fortran
- ▶ For both reading (old and new) and writing (new) programs
- ▶ Showing common idioms
- ▶ Illustrating and demonstrating many of the extensions introduced in the more recent standards
- ▶ Illustrating best practices
- ▶ Blaming bad ones
- ▶ Making you aware of the typical traps

Our Aims



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- ▶ Neither a substitute for personal practice



Introduction

Fortran Basics

- My First Fortran Program

- Compiling and Linking Your First Program

- Making Choices

- More Types and Choices

- Wrapping it Up 1

More Fortran Basics

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My First Scientific Program in Fortran



! roots of a 2nd degree equation with real coefficients

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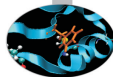
  print *, 'Solving ax^2+bx+c=0, enter a, b, c:'
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  delta = sqrt(b**2 - 4.0*a*c) ! square root of discriminant
  x1 = -b + delta
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end program second_degree_eq
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My First Scientific Program in Fortran



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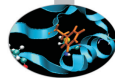
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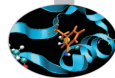
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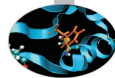
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 - ▶ Variable contents
 - ▶ Algorithms
 - ▶ Assumptions
 - ▶ Tricks



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- ▶ Best practice: do comment your code!
 - ▶ Variable contents
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 - ▶ Tricks
- ▶ Best practice: do not over-comment your code!
 - ▶ Obvious comments obfuscate code and annoy readers
 - ▶ **! square root of discriminant** is a bad example

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Program Units: Main Program



- ▶ Fortran code is organized in program units
 - ▶ Main program
 - ▶ Procedures (subroutines and functions)
 - ▶ Modules
 - ▶ More on this later...

Program Units: Main Program



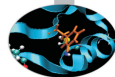
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- ▶ Best practice: always mark unit beginning and ending with its type and name
 - ▶ Makes your readers (including you) happier

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- ▶ **real :: x1, x2** declares two variables
 - ▶ Named memory locations where values can be stored
 - ▶ Declared by specifying a data type, an optional attribute list, and a comma-separated list of names
 - ▶ On most CPUs (notably x86), **real** means that **x1** and **x2** host IEEE single precision (i.e. 32 bits) floating point values



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 - ▶ Permitted characters: **a-z, A-Z, 0-9, _**
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- ▶ Beware: Fortran is CaSe insenSITIVE!

Implicit Declarations



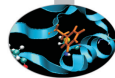
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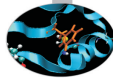


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- ▶ By default, Fortran assumes that variables not appearing in any declaration statement are implicitly declared as follows:
 - ▶ Variables whose name starts with **A - H** and **O - Z** are reals
 - ▶ Variables whose name starts with **I, J, K, L, M, N** are integers
- ▶ Best practice: it is strongly recommended to turn off implicit declarations with **`implicit none`**, at the beginning of each program unit
 - ▶ Improves readability and clarity: each variable has its type declared
 - ▶ Mistyped names can be caught by the compiler as undeclared variables

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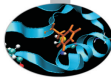
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A Few First Words on I/O



- ▶ The bare minimum: textual input output from/to the user terminal
 - ▶ `read(*,*)` and `read *`, `read`
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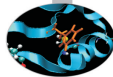
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- ▶ Enough for now, disregard details

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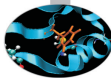
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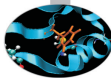
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- ▶ **x1 = x1 + delta** is a statement assigning the value of expression **x1 + delta** to variable **x1**
- ▶ By the way, expressions can be passed as argument to functions, as to **sqrt ()**: their value will be computed and passed to the function



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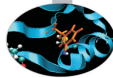
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What a Compiler Is



- ▶ Fortran lets you write programs in a high-level, human-readable language
- ▶ Computer CPUs do not directly understand this language
- ▶ You need to translate your code into machine-level instructions for your CPU architecture
- ▶ **Compilers take care of that translation and generate machine code that can be actually executed by a CPU**

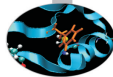
What a Compiler Does



- ▶ Compilers are sophisticated tools, made up of many components
- ▶ When compiler is invoked to generate executable code, three main steps are performed:
 1. parsing of source files, various kinds of analysis and transformations, optimization and *assembly* files creation
 2. machine-code generation and object file creation
 - ▶ an object file is an organized collection of all symbols (variables, functions...) used or referenced in the code
 3. linking and executable creation
- ▶ Options are provided to execute each step separately, take a look at the manual of your favourite compiler, there's a lot to learn!

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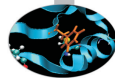


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```
user@cineca$> gfortran second_degree_eq.f90
```

An executable file named **a.out** (**a.exe** under Windows) will be generated

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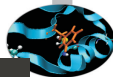
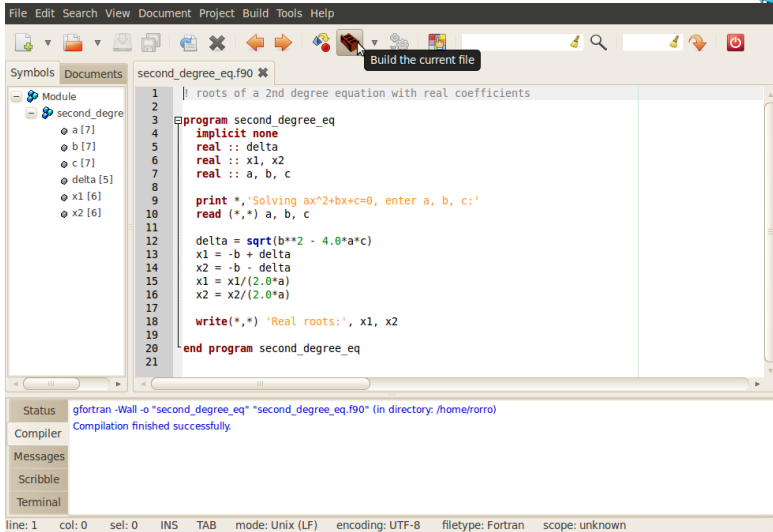
- ▶ Run the program under GNU/Linux with:

```
user@cineca$> ./a.out
```

or under Windows with:

```
C:\Documents and Settings\user> a.exe
```

Do You Like IDEs? Geany

File Edit Search View Document Project Build Tools Help

Build the current file

second_degree_eq.f90

```

1  ! roots of a 2nd degree equation with real coefficients
2
3
4  program second_degree_eq
5    implicit none
6    real :: delta
7    real :: x1, x2
8    real :: a, b, c
9
10   print *, 'Solving ax^2+bx+c=0, enter a, b, c:'
11   read (*,*) a, b, c
12
13   delta = sqrt(b**2 - 4.0*a*c)
14   x1 = -b + delta
15   x2 = -b - delta
16   x1 = x1/(2.0*a)
17   x2 = x2/(2.0*a)
18
19   write(*,*) 'Real roots:', x1, x2
20
21 end program second_degree_eq
  
```

Status: gfortran -Wall -o "second_degree_eq" "second_degree_eq.f90" (in directory: /home/orroro)
 Compiler: Compilation finished successfully.
 Messages:
 Scribble
 Terminal

line: 1 col: 0 sel: 0 INS TAB mode: Unix (LF) encoding: UTF-8 filetype: Fortran scope: unknown



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More Types and Choices

Wrapping it Up 1

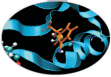
More Fortran Basics

Integer Types and Iterating

More on Compiling and Linking

Homeworks

Fixing a Defect



- User wants to solve $x^2 + 1 = 0$

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 - ▶ Enters: 1, 0, 1

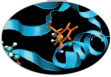


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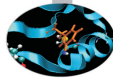
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- ▶ Let's avoid this, by changing from:

```
delta = sqrt(b**2 - 4.0*a*c)
```

to:

```
delta = b**2 - 4.0*a*c  
if (delta < 0.0) then  
    stop  
end if  
delta = sqrt(delta)
```

- ▶ Try it now!



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delta = sqrt(delta)
```

- ▶ Try it now!
- ▶ Did you check that normal cases still work? Good.

Conditional Statement



- ▶ **if** (*logical-condition*) **then**
 block of statements
end if
 - ▶ Executes *block of statements* only if *logical-condition* is true
 - ▶ Comparison operators: == (equal), /= (not equal), >, <, >=, <=
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```
if (delta < 0.0) then  
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endif
```

to:

```
if (delta < 0.0) stop 'No real roots!'
```

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- In general, Fortran disregards white space, but proper indentation visualizes program control flow



Introduction

Fortran Basics

My First Fortran Program

Compiling and Linking Your First Program

Making Choices

More Types and Choices

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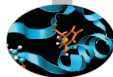
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Let's Refactor Our Program (and Test it!)



! roots of a 2nd degree equation with real coefficients

```
program second_degree_eq
  implicit none
  real :: delta
  real :: rp
  real :: a, b, c

  print *, 'Solving ax^2+bx+c=0, enter a, b, c: '
  read(*,*) a, b, c

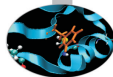
  delta = b*b - 4.0*a*c
  if (delta < 0.0) stop 'No real roots!'
  delta = sqrt(delta)/(2.0*a)

  rp = -b/(2.0*a)

  print *, 'Real roots: ', rp+delta, rp-delta

end program second_degree_eq
```

And Now Make it More Complex!



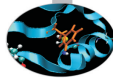
! roots of a 2nd degree equation with real coefficients

```
program second_degree_eq
  implicit none
  real :: delta, rp, a, b, c
  logical :: rroots

  print *, 'Solving ax^2+bx+c=0, enter a, b, c: '
  read(*,*) a, b, c
  delta = b*b - 4.0*a*c
  rroots = .true.
  if (delta < 0.0) then
    delta = -delta
    rroots = .false.
  end if
  delta = sqrt(delta)/(2.0*a)
  rp = -b/(2.0*a)
  if (rroots) then
    print *, 'Real roots: ', rp+delta, rp-delta
  else
    print *, 'Complex roots: ', rp, '+', delta, 'i ', &
      rp, '-', delta, 'i'
  end if
end program second_degree_eq
```



- ▶ **logical** type represents logical values
 - ▶ Can be **.true.** or **.false.**



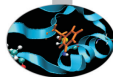
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- ▶ Allows for choosing between alternative paths

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- ▶ Again, use proper indentation

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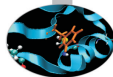
  print *, 'Solving ax^2+bx+c=0, enter a, b, c: '
  read(*,*) a, b, c
  delta = b*b - 4.0*a*c
  rroots = .true.
  if (delta < 0.0) then
    delta = -delta
    rroots = .false.
  end if
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    print *, 'Complex roots: ', rp, '+', delta, 'i ', &
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  end if
end program second_degree_eq

```


More Types and Choices



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 - ▶ Can be **.true.** or **.false.**
- ▶ **else** has to appear inside an **if () then/end if** pair, and the following statements up to **end if** are executed when the logical condition is false
- ▶ Allows for choosing between alternative paths
- ▶ Again, use proper indentation
- ▶ And Fortran statements cannot exceed one line, unless it ends with an **&**



! roots of a 2nd degree equation with real coefficients

```

program second_degree_eq
  implicit none
  real :: delta, rp, a, b, c
  logical :: rroots

  print *, 'Solving ax^2+bx+c=0, enter a, b, c: '
  read(*,*) a, b, c
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  delta = sqrt(delta)/(2.0*a)
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  if (rroots) then
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  else
    print *, 'Complex roots: ', rp, '+', delta, 'i ', &
      rp, '-', delta, 'i'
  end if
end program second_degree_eq

```

Let's Make it as Complex as Possible!



! roots of a 2nd degree equation with real coefficients

```

program second_degree_eq
  implicit none
  complex :: delta
  complex :: z1, z2
  real    :: a, b, c

  print *, 'Solving ax^2+bx+c=0, enter a, b, c: '
  read(*,*) a, b, c

  delta = b*b - 4.0*a*c
  delta = sqrt(delta)

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Complex Numbers



- ▶ Fortran has **complex** type:
 - ▶ hosting two real values, real and imaginary parts



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- ▶ Fortran has **complex** type:
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- ▶ Most math functions like **sqrt()** work for complex type too!
 - ▶ Returning correct results, instead of NaNs
- ▶ And so do **read**, **write**, and **print**
- ▶ **(1.5, 2.3)** is *Fortranese* for $1.5 + 2.3i$



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  real     :: a, b, c

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  print *, 'Roots: ', z1, z2

end program second_degree_eq
```


Making it More Robust



- What if user inputs zeroes for a or a and b ?

Making it More Robust



- ▶ What if user inputs zeroes for a or a and b ?
- ▶ Let's prevent these cases, inserting right after input:

```
if (a == 0.0) then
  if (b == 0.0) then
    if (c == 0.0) then
      write(0,*) 'A trivial identity!'
    else
      write(0,*) 'Plainly absurd!'
    end if
  else
    write(0,*) 'Too simple problem!'
  end if
stop
end if
```



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- Can you see the program logic?

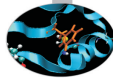


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```

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- ▶ Try it now!
- ▶ Did you check that normal cases still work? Good.

Miscellaneous remarks



- ▶ Nested **ifs** can be a problem
 - ▶ **else** marries innermost **if () then/end if** pair
 - ▶ Proper indentation is almost mandatory to sort it out

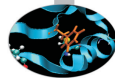


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- ▶ What's this **write(0,*)** stuff?
 - ▶ **write()** and **read()** let you specify an output (input) file 'handle' called a unit
 - ▶ Unit 0 is usually connected to a special file, mandatory for error messages to the terminal (e.g. UNIX standard error)
 - ▶ By the way, **write(*,*)** is a system independent idiom for what you'll often find written as **write(6,*)**
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 - ▶ And **stop error-message** is equivalent to: **write(0,*) error-message**
stop
- ▶ Best practice: if your program has to fail, always have it fail in a controlled way

Sorting it Out



► Let's give names to `if` constructs:

```
no2nd: if (a == 0.0) then
  nolst: if (b == 0.0) then
    no0th: if (c == 0.0) then
      write(0,*) 'A trivial identity!'
    else no0th
      write(0,*) 'Plainly absurd!'
    end if no0th
  else nolst
    write(0,*) 'Too simple problem!'
  end if nolst
  stop
end if no2nd
```



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  end if nolst
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end if no2nd
  
```

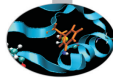
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- Names are for readability purposes only, do not enforce pairing rules

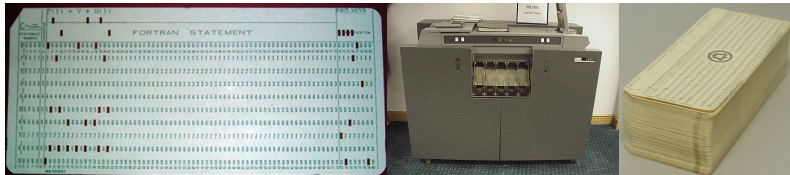


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```

- Giving names to constructs makes program logic more explicit
- Names are for readability purposes only, do not enforce pairing rules
- Best practice: always give names to constructs which span many lines of code or are deeply nested

Fortran Code, in the Beginning of Times



- ▶ The one on the left, is the statement $Z(I) = Y + W(I)$
- ▶ The one in the middle, is an IBM punch card reader
- ▶ The one on the right, is a complete Fortran source program
- ▶ But you'll only encounter these in museums, nowadays



C ROOTS OF A 2ND DEGREE EQUATION WITH REAL COEFFICIENTS

```
PROGRAM EQ2DEG
```

```
IMPLICIT NONE
```

```
REAL DELTA
```

```
REAL RP
```

```
REAL A, B, C
```

```
PRINT *, 'SOLVING  $AX^2+BX+C=0$ , ENTER A, B, C: '
```

```
READ(*,*) A, B, C
```

```
DELTA = B*B - 4.0*A*C
```

```
IF (DELTA.LT.0.0) STOP 'NO REAL ROOTS!'
```

```
DELTA = SQRT(DELTA) / (2.0*A)
```

```
RP = -B / (2.0*A)
```

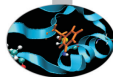
```
PRINT *, 'REAL ROOTS: ', RP+DELTA, RP-DELTA
```

```
END
```



- ▶ Code is all capitals
 - ▶ First computers had only uppercase letters
- ▶ Fixed source form
 - ▶ The legacy of punch cards
 - ▶ Comment lines must be marked with a `C` or `*` in first column
 - ▶ First six columns on each line are reserved for labels and to mark continuation lines
 - ▶ Columns after the 72nd are ignored (cause of really nasty bugs!)
- ▶ No double colon on variable declarations
 - ▶ And no way to initialize a variable at declaration, for that matter
 - ▶ More on this later
- ▶ And this example is not that different...

A Bottle of Fortran, Vintage Year 1963



```

C      SOLUTION OF QUADRATIC EQUATION
C      (P. 122 OF A FORTRAN PRIMER BY E. ORGANICK)
1 READ INPUT TAPE 5, 51, ANAME, N
51 FORMAT(A6,I2)
   WRITE OUTPUT TAPE 6,52, ANAME
52 FORMAT(1H1,33HROOTS OF QUADRATIC EQUATIONS FROM A6)
   DO 21 I = 1, N
   READ INPUT TAPE 5, 53, A, B, C
53 FORMAT(3F10.2)
   WRITE OUTPUT TAPE 6,54, I, A, B, C
54 FORMAT(1H0,8HSET NO. I2/5H A = F8.2,12X,4HB = F8.2,12X,4HC = F8.2)
   IF(A) 10, 7, 10
7 RLIN = -C/B
   WRITE OUTPUT TAPE 6, 55, RLIN
55 FORMAT(7H LINEAR,25X,4HX = F10.3)
   GO TO 21
10 D = B**2 - 4.*A*C
   IF(D) 12, 17, 17
12 COMPR = -B/(2.*A)
   COMP1 = SQRTF(-D)/(2.*A)
   COMP2= -COMP1
   WRITE OUTPUT TAPE 6, 56, COMPR, COMP1, COMP2
56 FORMAT(8H COMPLEX,21X,7HR(X1)= F10.3,11X,7HI(X1)= F10.3,/1H ,28X,
17HR(X2)= F10.3,11X,7HI(X2)= F10.3)
16 GO TO 21
17 REAL1 = (-B + SQRTF(D))/(2.*A)
   REAL2 = (-B - SQRTF(D))/(2.*A)
20 WRITE OUTPUT TAPE 6, 57, REAL1, REAL2
57 FORMAT(6H REAL 25X,5HX1 = F10.3,13X,5HX2 = F10.3)
21 CONTINUE
   WRITE OUTPUT TAPE 6, 58, ANAME
58 FORMAT(8H0END OF A6)
   GO TO 1
END

```


Best Practice: Free Yourself



- ▶ Write new code in free source form
 - ▶ No limits on beginning of program statements
 - ▶ Each line may contain up to 132 default characters
 - ▶ Comments can be added at end of line
 - ▶ And it comes for free: just give your source file name an **.f90** extension
- ▶ Use new language features
 - ▶ Like new styles for declarations
 - ▶ Or naming of constructs
 - ▶ They are more powerful and readable
- ▶ We'll focus on modern Fortran programming style
 - ▶ Making you aware of differences you are most likely to encounter
 - ▶ Look at compiler manuals or reference books to tame very old codes



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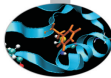
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A Fortran Program is Made of: I



- ▶ Comments
 - ▶ Compiler disregards them, but humans do not
 - ▶ Please, use them
 - ▶ Do not abuse them, please
- ▶ Program units
 - ▶ One, at least: **program**
 - ▶ Some of them (functions) are intrinsic to the language
- ▶ Variables
 - ▶ Named memory location you can store values into
 - ▶ Must be declared
- ▶ Variables declarations
 - ▶ Give name to memory location you can store values into
 - ▶ An initial value can be specified

A Fortran Program is Made of: II



- ▶ Expressions
 - ▶ Compute values to store in variables
 - ▶ Compute values to pass to functions and statements
- ▶ Statements
 - ▶ Units of executable work
 - ▶ Whose execution can be controlled by other constructs
- ▶ **if** statements and constructs
 - ▶ Allow for conditional and alternative execution
 - ▶ For both single statements and blocks of



- ▶ Use free source form
- ▶ **implicit none** statement
 - ▶ Turn off implicit declarations
- ▶ Use proper indentation
 - ▶ Compilers don't care about
 - ▶ Readers visualize flow control
- ▶ Give names to complex control structures, readers will appreciate
- ▶ Do non-regression testing
 - ▶ Whenever functionalities are added
 - ▶ Whenever you rewrite a code in a different way
- ▶ Fail in a controlled way
 - ▶ Giving feedback to humans



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Fortran Basics

More Fortran Basics

- My First Fortran Functions

- Making it Correct

- Making it Robust

- Copying with Legacy

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My First Fortran Functions



```
function theta(x) !Heaviside function, useful in DSP
  implicit none
  real :: theta
  real :: x

  theta = 1.0
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end function theta
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function sinc(x) !sinc function as used in DSP
  implicit none
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function rect(t, tau) !generalized rectangular function, useful in DSP
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  real :: rect
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  abs_t = abs(t)
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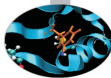
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Functions and their Definition



- ▶ Functions are program units
 - ▶ Function name must be a legal Fortran name
 - ▶ Functions specialty is performing computations and returning a value

My First Fortran Functions



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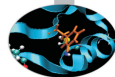
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 - ▶ Could be declared on the function heading, but it's less flexible and less readable
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- ▶ How to return a value
 - ▶ Just assign it to the function name, as if it were a variable
 - ▶ But this doesn't force function termination
 - ▶ Multiple assignments can be done
 - ▶ The last assigned value before function execution is complete will be returned

My First Fortran Functions



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 - ▶ Declared like variables inside the function
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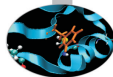


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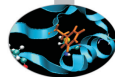
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- ▶ What if a dummy argument has the same name of a variable elsewhere in the program?
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- ▶ Variables can be defined inside functions
 - ▶ Again, they are local, thus completely independent from the rest of the program

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- ▶ Fortran sports a wealth (over a hundred!) of predefined functions and procedures
- ▶ These are termed *intrinsic*
 - ▶ **acos(x)** returns the arc cosine of x such that $|x| \leq 1$ in the range $0 \leq \arccos(x) \leq \pi$
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- ▶ What's this **external** keyword?
- ▶ It's one of the many attributes you can give to something you define
 - ▶ **external** tells the compiler **theta** is an external (i.e. non intrinsic) function
 - ▶ So the compiler is not forced to guess what it is from its use
 - ▶ And that way, masters can override intrinsic functions

My First Fortran Functions



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The `parameter` Attribute



- ▶ The `parameter` attribute is used to declare named constants
 - ▶ i.e. variables that cannot be modified after initialization (compiler will bark if you try)

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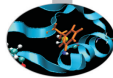


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 - ▶ i.e. variables that cannot be modified after initialization (compiler will bark if you try)
- ▶ In initialization expressions:
 - ▶ only constants (possibly other `parameters`) can be used
 - ▶ only intrinsic operators or functions are allowed
- ▶ Best practice: always give name to constants
 - ▶ Particularly if unobvious, like `1.0/137.0`
 - ▶ It also helps to centralize updates (well, not for π)



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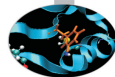


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 - ▶ Helps to tame complexity
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Hands-on Session #2



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end function theta
```

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DSP test program



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```
program dsp_test
```

```
    real :: i,j,k
```

```
end program dsp_test
```

DSP test program



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```
program dsp_test  
  
  real :: i,j,k  
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  real, external :: theta, sinc, rect
```

```
end program dsp_test
```



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program dsp_test

  real :: i,j,k
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  read(*,*) i, j, k

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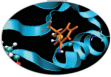
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  rtheta = theta(i)
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  rtheta = theta(i)
  rsinc = sinc(i)
  rrect = rect(j, k)

  write(*,*) 'theta(' , i, ') = ', rtheta
  write(*,*) 'sinc(' , i , ') = ', rsinc
  write(*,*) 'rect(' , j, ', ', k, ') = ', rrect

end program dsp_test
  
```


Testing DSP Functions



- ▶ Let's build our test program putting all together:

```
user@cineca$> gfortran dsp.f90 dsp_test.f90 -o dsp_test
```

- ▶ `-o` option specifies the name **dsp_test** for the executable



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theta( -3.1415927      ) =    0.0000000
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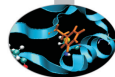
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- ▶ Something is going wrong, isn't it?
 - ▶ Seems like one function changed its actual argument!



- ▶ Let's put the code in a file named `dsp.f90`
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State Your Intent!



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function theta(x) !Heaviside function, useful in DSP
  implicit none
  real :: theta
  real, intent(in) :: x

  theta = 1.0
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end function theta
```

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Testing DSP Functions Again



- Try to recompile `dsp`. £90...

Testing DSP Functions Again



- ▶ Try to recompile `dsp.f90`...
- ▶ Now compiler will check if you respect your stated intents:

```
user@cineca$> gfortran -o dsp_test dsp_test.f90 dsp.f90
dsp.f90:16:2:

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Error: Cannot assign to INTENT(IN) variable 'x' at (1)
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Testing DSP Functions Again



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- ▶ Got a compiler error message? Good!

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 - ▶ **intent (in)** for those you only plan to read values from

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 - ▶ (And if you pass a constant or expression, an unnamed variable is created for you)
 - ▶ When a dummy argument is assigned to, the actual argument is assigned to
 - ▶ This is a great feature, but a source of bugs too (particularly for C programmers)
 - ▶ And it's one possible *side effect* you'll have to watch over
- ▶ Best practice: always give dummy arguments the proper attribute
 - ▶ **intent (in)** for those you only plan to read values from
 - ▶ **intent (out)** for those you only plan to write values to

It's Pass by Reference!



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My First Fortran Functions Fixed!



```
function theta(x) !Heaviside function, useful in DSP
  implicit none
  real :: theta
  real, intent(in) :: x

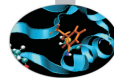
  theta = 1.0
  if (x < 0.0 ) theta = 0.0
end function theta
```

```
function sinc(x) !sinc function as used in DSP
  implicit none
  real :: sinc, xpi
  real, intent(in) :: x
  real, parameter :: pi = acos(-1.0)

  xpi = x*pi
  sinc = 1.0
  if (xpi /= 0.0) sinc = sin(xpi)/xpi
end function sinc
```

```
function rect(t, tau) !generalized rectangular function, useful in DSP
  implicit none
  real :: rect
  real, intent(in) :: t, tau
  real :: abs_t, half_tau
  real, external :: theta

  abs_t = abs(t)
  half_tau = 0.5*tau
  rect = 0.5
  if (abs_t /= half_tau) rect = theta(half_tau-abs_t)
end function rect
```



► Way much better!

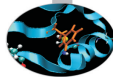
```
user@cineca$> gfortran -o dsp_test dsp_test.f90 dsp.f90
user@cineca$> ./dsp_test
Enter i, j, k:
-1 0 1
theta( -1.0000000      ) =    0.0000000
sinc(  -1.0000000      ) =  -2.78275341E-08
rect(   0.0000000      ,   1.0000000      ) =    1.0000000
```



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- Now comment out `real :: i, j, k` in `dsp_test.f90`, recompile and rerun



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```

- Now comment out `real :: i, j, k` in `dsp_test.f90`, recompile and rerun
- Now add `implicit none` to `dsp_test.f90` and do it again



Introduction

Fortran Basics

More Fortran Basics

My First Fortran Functions

Making it Correct

Making it Robust

Copying with Legacy

Wrapping it Up 2

Integer Types and Iterating

More on Compiling and Linking

Homeworks



- Try to pass **integer** variables as actual arguments to **theta()**, **sinc()**, and **rect()**



- ▶ Try to pass **integer** variables as actual arguments to **theta()**, **sinc()**, and **rect()**
- ▶ Got some surprising behavior?

Ignorance is Evil



- ▶ Try to pass **integer** variables as actual arguments to **theta()**, **sinc()**, and **rect()**
- ▶ Got some surprising behavior?
- ▶ Our testing program doesn't know enough about external functions it is calling
 - ▶ It is knowledgeable about return types
 - ▶ It is totally ignorant about argument types



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 - ▶ It is knowledgeable about return types
 - ▶ It is totally ignorant about argument types
- ▶ We can make it aware using **interface** blocks



```
program dsp
```

```
  implicit none
```

```
  real :: i,j,k
```

```
  real, external :: theta, sinc, rect
```

```
  print *, 'Enter i, j, k:'
```

```
  read(*,*) i, j, k
```

```
  write(*,*) 'theta(', i, ')= ', theta(i)
```

```
  write(*,*) 'sinc(', i, ')= ', sinc(i)
```

```
  write(*,*) 'rect(', j, ', ', k, ')= ', rect(j,k)
```

```
end program dsp
```



```

program dsp

  implicit none

  real :: i,j,k

  interface
    function theta(x)
      real :: theta, x
    end function theta
  end interface

  interface
    function sinc(x)
      real :: sinc, x
    end function sinc
  end interface

  interface
    function rect(t, tau)
      real :: rect, t, tau
    end function rect
  end interface

  print *, 'Enter i, j, k:'
  read(*,*) i, j, k

  write(*,*) 'theta(', i, ') = ', theta(i)
  write(*,*) 'sinc(', i, ') = ', sinc(i)
  write(*,*) 'rect(', j, ', ', k, ') = ', rect(j,k)

end program dsp
  
```



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 - ▶ Just type it in each program unit calling dsp functions



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 - ▶ But life is too short to modify interfaces spread around 56 program units

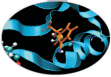


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 - ▶ Just type it in each program unit calling dsp functions
 - ▶ Or, if your life is too short for typing, copy and paste it
 - ▶ But life is too short to modify interfaces spread around 56 program units
 - ▶ Good, but still error prone, no better way?

use Modules, Instead!



- Modules are the Fortran way to complete and robust management of sets of related routines and more



```

module dsp
  implicit none
contains
  function theta(x) !Heaviside function, useful in DSP
    real :: theta
    real, intent(in) :: x

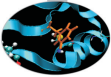
    theta = 1.0
    if (x < 0.0 ) theta = 0.0
  end function theta

  function sinc(x) !sinc function as used in DSP
    real :: sinc, xpi
    real, intent(in) :: x
    real, parameter :: pi = acos(-1.0)

    xpi = x*pi
    sinc = 1.0
    if (xpi /= 0.0) sinc = sin(xpi)/xpi
  end function sinc

  function rect(t, tau) !generalized rectangular function, useful in DSP
    real :: rect
    real, intent(in) :: t, tau
    real :: abs_t, half_tau

    abs_t = abs(t)
    half_tau = 0.5*tau
    rect = 0.5
    if (abs_t /= half_tau) rect = theta(half_tau-abs_t)
  end function rect
end module dsp
  
```



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  function theta(x) !Heaviside function, useful in DSP
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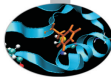
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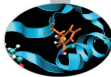
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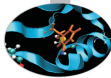
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  end function rect
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 - ▶ If you have a set of related procedures, always make a module
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- ▶ But there is a lot more to say about modules

Modules Give You Fine Control



- ▶ A nice colleague handed you the `dsp` module...
- ▶ but you prefer your own version of `rect ()` , which returns 1 on borders:
 - ▶ don't change the module source

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 - ▶ **use dsp, only : theta, sinc**
and keep using your own **rect ()**

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use dsp, heaviside=>theta



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Managing Wrong Arguments

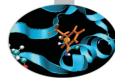


```
function rect(t, tau)
  implicit none
  real :: rect
  real, intent(in) :: t, tau
  real :: abs_t, half_tau

  abs_t = abs(t)
  half_tau = 0.5*tau
  rect = 0.5
  if (abs_t /= half_tau) rect = theta(half_tau-abs_t)
end function rect
```

- What if `rect ()` is passed a negative argument for `tau`?

Managing Wrong Arguments



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 - ▶ Wrong results
- ▶ Taking the absolute value of **tau** it's a possibility



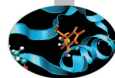
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end function rect
  
```

- ▶ What if **rect ()** is passed a negative argument for **tau**?
 - ▶ Wrong results
- ▶ Taking the absolute value of **tau** it's a possibility
- ▶ But not a good one, because:
 - ▶ a negative rectangle width is nonsensical
 - ▶ probably flags a mistake in the calling code
 - ▶ and a zero rectangle width is also a problem

Failing Predictably



```
function rect(t, tau)
  implicit none
  real :: rect
  real, intent(in) :: t, tau
  real :: abs_t, half_tau

  if (tau <= 0.0) stop 'rect() non positive second argument'
  abs_t = abs(t)
  half_tau = 0.5*tau
  rect = 0.5
  if (abs_t /= half_tau) rect = theta(half_tau-abs_t)
end function rect
```

- A known approach...



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function rect(t, tau)
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end function rect
  
```

- ▶ A known approach...
- ▶ but too rude!
 - ▶ No clue at the argument value
 - ▶ No clue at which call to `rect()` was wrong
 - ▶ And stopping a program in a procedure, called by another procedure, called by another procedure, ..., is widely reputed bad programming practice

A Better Approach



```

module dsp
  implicit none
  integer :: dsp_info
  integer, parameter :: DSPERR_DOMAIN = 1
contains
  function theta(x) !Heaviside function, useful in DSP
  ! code as in previous examples...
  end function theta

  function sinc(x) !sinc function as used in DSP
  ! code as in previous examples...
  end function sinc

  function rect(t, tau) !generalized rectangular function, useful in DSP
  real :: rect
  real, intent(in) :: t, tau
  real :: abs_t, half_tau

  if (tau <= 0.0) then
    dsp_info = DSPERR_DOMAIN
    rect = 0.0
    return
  end if

  abs_t = abs(t)
  half_tau = 0.5*tau
  rect = 0.5
  if (abs_t /= half_tau) rect = theta(half_tau-abs_t)
end function rect
end module dsp

```



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end function rect
end module dsp
  
```



- Yes, a module can define variables, too

More Module Power, and More Types



- ▶ Yes, a module can define variables, too
- ▶ And they will be accessible to all program units using it



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end function rect
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```

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- ▶ Yes, a module can define variables, too
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- ▶ And yes, **integer** it's another Fortran type
 - ▶ For variables hosting integer numerical values
 - ▶ More on this later...



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    return
  end if

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end module dsp
  
```


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- ▶ And they will be accessible to all program units using it
- ▶ And yes, **integer** it's another Fortran type
 - ▶ For variables hosting integer numerical values
 - ▶ More on this later...
- ▶ And yes, **return** forces function execution to terminate and return to calling unit



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  ! code as in previous examples...
  end function sinc

  function rect(t, tau) !generalized rectangular function, useful in DSP
  real :: rect
  real, intent(in) :: t, tau
  real :: abs_t, half_tau

  if (tau <= 0.0) then
    dsp_info = DSPERR_DOMAIN
    rect = 0.0
    return
  end if

  abs_t = abs(t)
  half_tau = 0.5*tau
  rect = 0.5
  if (abs_t /= half_tau) rect = theta(half_tau-abs_t)
end function rect
end module dsp
  
```

Error Management Strategy



- ▶ Set a module variable to a constant corresponding to the error class
- ▶ And return a sensible result



- ▶ Set a module variable to a constant corresponding to the error class
- ▶ And return a sensible result
- ▶ Then a wise user would do something like this:

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dsp_info = 0
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```

- ▶ Note: even if Fortran ignores case, constants are often highlighted using all capitals

A Widely Used Approach



```

module dsp
  implicit none
  integer, parameter :: DSPERR_DOMAIN = 1
contains

  ! ...

  function rect(t, tau, info) !generalized rectangular function, useful in DSP
    real :: rect
    real, intent(in) :: t, tau
    integer, intent(out) :: info
    real :: abs_t, half_tau

    info = 0
    if (tau <= 0.0) then
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      return
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Using Arguments to Return Error Codes



- ▶ Set a dedicated argument to a constant corresponding to the error class
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Using Arguments to Return Error Codes



- ▶ Set a dedicated argument to a constant corresponding to the error class
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```
r = rect(x, width, rect_info)
if (rect_info == DSPERR_DOMAIN) then
    ! take corrective action or fail gracefully
end if
```

- ▶ But this is annoying when the arguments are guaranteed to be correct
 - ▶ **info** can be given the **optional** attribute
 - ▶ and omitted when you feel it's safe: **rect(x, 5.0)**

Making Argument Optionals



```

module dsp
  implicit none
  integer, parameter :: DSPERR_DOMAIN = 1
contains

  ! ...

  function rect(t, tau, info) !generalized rectangular function, useful in DSP
    real :: rect
    real, intent(in) :: t, tau
    integer, intent(out), optional :: info
    real :: abs_t, half_tau

    if (present(info)) info = 0
    if (tau <= 0.0) then
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    end if

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```

Making Argument Optionals



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module dsp
  implicit none
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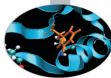
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```

Total Robustness

- ▶ Your platform could support IEEE floating point standard
 - ▶ Most common ones do, at least in a good part



Total Robustness

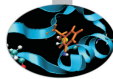


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 - ▶ one of the arguments is a NaN
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- ▶ Best strategy: return a NaN and set **dsp_info** in these bad cases
 - ▶ And do it also for non positive values of **tau**
 - ▶ But then the floating point environment configuration should be checked, proper floating point exceptions set...



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- ▶ Best strategy: return a NaN and set **dsp_info** in these bad cases
 - ▶ And do it also for non positive values of **tau**
 - ▶ But then the floating point environment configuration should be checked, proper floating point exceptions set...
- ▶ Being absolutely robust is difficult
 - ▶ Too advanced stuff to cover in this course
 - ▶ But not an excuse, some robustness is better than none
 - ▶ It's a process to do in steps
 - ▶ Always comment in your code bad cases you don't cover yet!



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```

FUNCTION SINC(X)
  IMPLICIT NONE
  REAL SINC, X, XPI
  REAL PI
  PARAMETER (PI = 3.1415926)

  XPI = X*PI
  SINC = 1.0
  IF (XPI .NE. 0.0) SINC = SIN(XPI)/XPI
END

FUNCTION RECT(T, TAU)
  IMPLICIT NONE
  REAL RECT, T, TAU
  REAL ABS_T, HALF_TAU
  REAL THETA
  EXTERNAL THETA
  INTEGER DSPINFO
  COMMON /DSP/ DSPINFO

  IF (TAU .LE. 0.0) THEN
    DSPINFO = 1
    RECT = 0.0;
    RETURN
  END IF

  ABS_T = ABS(T)
  HALF_TAU = 0.5*TAU
  RECT = 0.5
  IF (ABS_T .NE. HALF_TAU) RECT = THETA(HALF_TAU-ABS_T)
END
  
```

Many Things are Missing



- ▶ Strange looking relational operators
- ▶ No attributes
 - ▶ Declarations spread over many lines, error prone
- ▶ No initialization expressions
 - ▶ You had to type in the actual number
- ▶ No **intent** i.e. no defense from subtle bugs
- ▶ No **interface**

Many Things are Missing



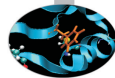
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 - ▶ To share you had to use **common** statements
 - ▶ And type in variable types and **common** statements in each unit
 - ▶ And the smallest mistake can turn into a nightmare

Many Things are Missing



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- ▶ No easy way to share variables among program units
 - ▶ To share you had to use **common** statements
 - ▶ And type in variable types and **common** statements in each unit
 - ▶ And the smallest mistake can turn into a nightmare
- ▶ Bottom line:
 - ▶ Is **common** good or bad? The jury is still out
 - ▶ We'll not cover them, but you'll encounter them
 - ▶ Read the fine print, or better switch to modules, they are **way much better**

Refurbishing Old Code



- ▶ You are lucky, and inherit a 4000 lines of code library, coming from the dark ages
 - ▶ Tested and tried

Refurbishing Old Code



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Refurbishing Old Code



- ▶ You are lucky, and inherit a 4000 lines of code library, coming from the dark ages
 - ▶ Tested and tried
- ▶ But no interface
 - ▶ Thus no compiler checks when you call it
 - ▶ And rewriting a working code in modern language is soooo dangerous...
- ▶ Modules come to rescue
 - ▶ They don't need to include the actual code
 - ▶ But they can publish an interface for code which is elsewhere
 - ▶ And then you can use the module in calling program units

Wrapping Old Code in a Module



```
module dspmod

  implicit none

  interface
    function theta(x)
      real :: theta
      real, intent(in) :: x
    end function theta
  end interface

  interface
    function sinc(x)
      real :: sinc
      real, intent(in) :: x
    end function sinc
  end interface

  interface
    function rect(t, tau)
      real :: rect
      real, intent(in) :: t, tau
    end function rect
  end interface

end module dspmod
```



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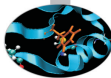
We Did Progress!



- ▶ A program can be subdivided in more source files
- ▶ Functions and their arguments
- ▶ Arguments are passed to functions by reference
- ▶ **intent** attribute is precious to prevent subtle bugs
- ▶ Intrinsic and external procedures are two different things
- ▶ **parameter** variables
- ▶ Explicit interfaces
- ▶ Modules allow complete management of procedures
- ▶ Modules allow access to variables from many program units
- ▶ Modules can be used to make proper use of legacy, reliable codes



- ▶ Always name constants
- ▶ Test every function you write
 - ▶ Writing specialized programs to do it
- ▶ Use language support and compiler to catch mistakes
- ▶ Use explicit interfaces
- ▶ Use modules
- ▶ Describe all attributes of a variable at declaration
- ▶ Anticipate causes of problems
 - ▶ Find a rational way to react
 - ▶ Fail predictably and in a user friendly way
 - ▶ Robustness it's a long way to do in steps
 - ▶ Comment in your code issues still to address



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► Euclid's Algorithm

1. Take two integers a and b
2. Let $r \leftarrow a \bmod b$
3. Let $a \leftarrow b$
4. Let $b \leftarrow r$
5. If b is not zero, go back to step 2
6. a is the GCD

► Let's implement it and learn some more Fortran



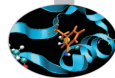
```
module number_theory
  implicit none
contains
  function gcd(a, b) ! Greatest Common Divisor
    integer :: gcd
    integer, intent(in) :: a, b
    integer :: gb, t

    gcd = a
    gb = b

    do
      t = mod(gcd,gb)
      gcd = gb
      if (t == 0) exit
      gb = t
    end do
  end function gcd

  function lcm(a, b) ! Least Common Multiple
    integer :: lcm
    integer, intent(in) :: a, b

    lcm = a*b/gcd(a,b)
  end function lcm
end module number_theory
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The Integer Type



- ▶ As we said, **integer** means that a value is an integer
 - ▶ Only integer values, positive, negative or zero
 - ▶ On most platforms, **integer** means a 32 bits value, ranging from -2^{31} to $2^{31} - 1$

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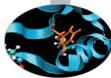
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 - ▶ Try with **kind(0)**, to know the size of a normal **integer**
 - ▶ And works for real values too, or values of any type, for that matter
 - ▶ More on this later
- ▶ Want to know more?
 - ▶ Intrinsic function **huge(0)** returns the greatest positive value an **integer** can assume
 - ▶ Again, we'll be back at this



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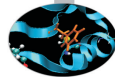
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```
module number_theory
  implicit none
  contains
    function gcd(a, b) ! Greatest Common Divisor
      integer :: gcd
      integer, intent(in) :: a, b
      integer :: gb, t

      gcd = a
      gb = b

      do
        t = mod(gcd, gb)
        gcd = gb
        if (t == 0) exit
        gb = t
      end do
    end function gcd

    function lcm(a, b) ! Least Common Multiple
      integer :: lcm
      integer, intent(in) :: a, b

      lcm = a*b/gcd(a,b)
    end function lcm
end module number_theory
```

Iterating with `do` . . . `end do`



► `do`

block of statements

`end do`

1. Executes again and again the *block of statements*
2. And does this forever...
3. ... unless **`exit`** is executed, forcing execution to proceed at code following `end do`

Iterating with `do` . . . `end do`



► `do`

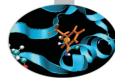
block of statements

`end do`

1. Executes again and again the *block of statements*
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► In this specific example:

Iterating with `do` . . . `end do`



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► In this specific example:

- the code following `end do` is the end of the function
- thus, we could use **`return`** instead of **`exit`**, which is legal,
- but generally regarded bad practice

Iterating with `do . . . end do`



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► In this specific example:

- the code following `end do` is the end of the function
 - thus, we could use `return` instead of `exit`, which is legal,
 - but generally regarded bad practice
- Best practice: do not bail out of a function from inside a loop, particularly a long one



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- ▶ Put the code in file `numbertheory.f90`
- ▶ Write a program to test both `gcd()` and `lcm()` on a pair of integer numbers
- ▶ Test it:
 - ▶ with pairs of small positive integers
 - ▶ with the following pairs: 15, 18; -15, 18; 15, -18; -15, -18; 0, 15; 15, 0; 0, 0

GCD & LCM: Try it Now!



```
module number_theory
  implicit none
contains
  function gcd(a, b) ! Greatest Common Divisor
    integer :: gcd
    integer, intent(in) :: a, b
    integer :: gb, t

    gcd = a
    gb = b

    do
      t = mod(gcd,gb)
      gcd = gb
      if (t == 0) exit
      gb = t
    end do
  end function gcd

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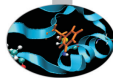
    lcm = a*b/gcd(a,b)
  end function lcm
end module number_theory
```



- ▶ Put the code in file `numbertheory.f90`
- ▶ Write a program to test both `gcd()` and `lcm()` on a pair of integer numbers
- ▶ Test it:
 - ▶ with pairs of small positive integers
 - ▶ with the following pairs: 15, 18; -15, 18; 15, -18; -15, -18; 0, 15; 15, 0; 0, 0
- ▶ In some cases, we get wrong results or runtime errors
 - ▶ Euclid's algorithm is only defined for positive integers

Let's Generalize to the Whole Integer Set

- ▶ $\text{gcd}(a, b)$ is non negative, even if a or b is less than zero
 - ▶ Taking the absolute value of a and b using `abs()` will do





```

module number_theory
  implicit none
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  function gcd(a, b) ! Greatest Common Divisor
    integer :: gcd
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    integer :: gb, t

    gcd = abs(a)
    gb = abs(b)

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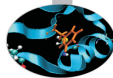
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end module number_theory

```

Let's Generalize to the Whole Integer Set

- ▶ $\text{gcd}(a, b)$ is non negative, even if a or b is less than zero
 - ▶ Taking the absolute value of a and b using `abs()` will do
- ▶ $\text{gcd}(a, 0)$ is $|a|$
 - ▶ Conditional statements will do



GCD & LCM: Dealing with 0 and Negatives



```
module number_theory
  implicit none
contains
  function gcd(a, b) ! Greatest Common Divisor
    integer :: gcd
    integer, intent(in) :: a, b
    integer :: gb, t

    gcd = abs(a)
    gb = abs(b)

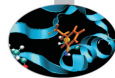
    if (a == 0) gcd = gb
    if (a == 0 .or. b == 0) return

    do
      t = mod(gcd, gb)
      gcd = gb
      if (t == 0) exit
      gb = t
    end do
  end function gcd

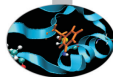
  function lcm(a, b) ! Least Common Multiple
    integer :: lcm
    integer, intent(in) :: a, b

    lcm = a*b/gcd(a,b)
  end function lcm
end module number_theory
```

Let's Generalize to the Whole Integer Set



- ▶ $\text{gcd}(a, b)$ is non negative, even if a or b is less than zero
 - ▶ Taking the absolute value of a and b using `abs()` will do
- ▶ $\text{gcd}(a, 0)$ is $|a|$
 - ▶ Conditional statements will do
- ▶ $\text{gcd}(0, 0)$ is 0
 - ▶ Already covered by the previous item, but let's pay attention to `lcm()`



```

module number_theory
  implicit none
contains
  function gcd(a, b) ! Greatest Common Divisor
    integer :: gcd
    integer, intent(in) :: a, b
    integer :: gb, t

    gcd = abs(a)
    gb = abs(b)

    if (a == 0) gcd = gb
    if (a == 0 .or. b == 0) return

    do
      t = mod(gcd, gb)
      gcd = gb
      if (t == 0) exit
      gb = t
    end do
  end function gcd

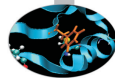
  function lcm(a, b) ! Least Common Multiple
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Let's Generalize to the Whole Integer Set



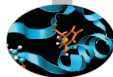
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 - ▶ `;` makes for two statements on the same line: but its use is only justified when space is at a premium, like in slides

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GCD & LCM: Try it Now!



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module number_theory
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contains
  function gcd(a, b) ! Greatest Common Divisor
    integer :: gcd
    integer, intent(in) :: a, b
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      t = mod(gcd,gb)
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```

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Beware of Type Ranges



- $a*b/\text{gcd}(a,b)$ same as $(a*b) / \text{gcd}(a,b)$

Beware of Type Ranges



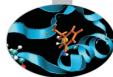
- ▶ $a*b/\gcd(a,b)$ same as $(a*b) / \gcd(a,b)$
- ▶ What if the result of a calculation cannot be represented in the given type?
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 - ▶ Best practice: be very careful of intermediate results

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- ▶ Easy fix: $\text{gcd}(a,b)$ is an exact divisor of b

GCD & LCM: Preventing Overflow



```

module number_theory
  implicit none
contains
  function gcd(a, b) ! Greatest Common Divisor
    integer :: gcd
    integer, intent(in) :: a, b
    integer :: gb, t

    gcd = abs(a)
    gb = abs(b)

    if (a == 0) gcd = gb
    if (a == 0 .or. b == 0) return

    do
      t = mod(gcd,gb)
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      if (t == 0) exit
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    integer :: lcm
    integer, intent(in) :: a, b

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    end if

    lcm = a*(b/gcd(a,b))
  end function lcm
end module number_theory

```

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 - ▶ on the following pairs: 15, 18; -15, 18; 15, -18; -15, -18; 0, 15; 15, 0; 0, 0
 - ▶ with the pair: 1000000, 1000000
 - ▶ and let's test also with: 1000000, 1000001



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Wider Integer Types



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 - ▶ `range(0)` returns 9, i.e. you can store 10^9 in an integer
 - ▶ but 64 bits wide integers can safely host 10^{18}
- ▶ `selected_int_kind(n)`:
 - ▶ returns a *kind type parameter* corresponding to an internal representation capable to host the value 10^n
 - ▶ or `-1` if none is wide enough
- ▶ `integer` accepts an optional *kind type parameter*
 - ▶ `integer(kind=selected_int_kind(9)) :: di` usually makes `di` a 32 bits wide variable
 - ▶ `integer(kind=selected_int_kind(18)) :: wi` makes `wi` a 64 bits wide variable
 - ▶ `integer(selected_int_kind(18)) :: wi` will also do

GCD & LCM: Let's Make Kind Explicit



```

module number_theory
  implicit none
contains
  function gcd9(a, b) ! Greatest Common Divisor
    integer(selected_int_kind(9)) :: gcd9
    integer(selected_int_kind(9)), intent(in) :: a, b
    integer(selected_int_kind(9)) :: gb, t

    gcd9 = abs(a)
    gb = abs(b)

    if (a == 0) gcd9 = gb
    if (a == 0 .or. b == 0) return

    do
      t = mod(gcd9, gb)
      gcd9 = gb
      if (t == 0) exit
      gb = t
    end do
  end function gcd9

  function lcm9(a, b) ! Least Common Multiple
    integer(selected_int_kind(9)) :: lcm9
    integer(selected_int_kind(9)), intent(in) :: a, b

    if (a == 0 .and. b == 0) then
      lcm9 = 0 ; return
    end if

    lcm9 = a*(b/gcd9(a,b))
  end function lcm9
end module number_theory

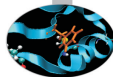
```

Being More General and Generic

- And let's add support for a wider integer range



GCD & LCM: Let's Add Headroom



```
! add right after: end function lcm9
```

```
function gcd18(a, b) ! Greatest Common Divisor
  integer(selected_int_kind(18)) :: gcd18
  integer(selected_int_kind(18)), intent(in) :: a, b
  integer(selected_int_kind(18)) :: gb, t
```

```
gcd18 = abs(a)
gb = abs(b)
```

```
if (a == 0) gcd18 = gb
if (a == 0 .or. b == 0) return
```

```
do
  t = mod(gcd18,gb)
  gcd18 = gb
  if (t == 0) exit
  gb = t
end do
```

```
end function gcd18
```

```
function lcm18(a, b) ! Least Common Multiple
  integer(selected_int_kind(18)) :: lcm18
  integer(selected_int_kind(18)), intent(in) :: a, b
```

```
if (a == 0 .and. b == 0) then
  lcm18 = 0 ; return
end if
```

```
lcm18 = a*(b/gcd18(a,b))
end function lcm18
```

Being More General and Generic



- ▶ And let's add support for a wider integer range
- ▶ Wait!
 - ▶ Now we have to remember to call the right function, depending on the integer kind
 - ▶ But this is not Fortran style: we didn't have to change the call to intrinsic **abs ()** , it's name is generic
 - ▶ Can we do better?

Being More General and Generic



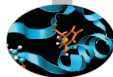
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- ▶ Yes, we can do better!
 - ▶ **interface** blocks come to rescue

GCD & LCM: Making it Generic



```

module number_theory
  implicit none

  private gcd9, lcm9, gcd18, lcm18

  interface gcd
    module procedure gcd9, gcd18
  end interface

  interface lcm
    module procedure lcm9, lcm18
  end interface

contains

  function gcd9(a, b) ! Greatest Common Divisor
    ! code as before
  end function gcd9

  function lcm9(a,b) ! Least Common Multiple
    ! code as before
  end function lcm9

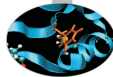
  function gcd18(a, b) ! Greatest Common Divisor
    ! code as before
  end function gcd18

  function lcm18(a,b) ! Least Common Multiple
    ! code as before
  end function lcm18

end module number_theory

```

Being More General and Generic



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```

module number_theory
  implicit none

  private gcd9, lcm9, gcd18, lcm18

  interface gcd
    module procedure gcd9, gcd18
  end interface

  interface lcm
    module procedure lcm9, lcm18
  end interface

contains

  function gcd9(a, b) ! Greatest Common Divisor
    ! code as before
  end function gcd9

  function lcm9(a,b) ! Least Common Multiple
    ! code as before
  end function lcm9

  function gcd18(a, b) ! Greatest Common Divisor
    ! code as before
  end function gcd18

  function lcm18(a,b) ! Least Common Multiple
    ! code as before
  end function lcm18

end module number_theory

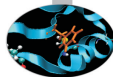
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  interface gcd
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  interface lcm
    module procedure lcm9, lcm18
  end interface

contains

  function gcd9(a, b) ! Greatest Common Divisor
    ! code as before
  end function gcd9

  function lcm9(a,b) ! Least Common Multiple
    ! code as before
  end function lcm9

  function gcd18(a, b) ! Greatest Common Divisor
    ! code as before
  end function gcd18

  function lcm18(a,b) ! Least Common Multiple
    ! code as before
  end function lcm18

end module number_theory

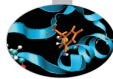
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Being More General and Generic



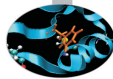
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- ▶ Best practices for robustness:

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 - ▶ write generic procedures, whenever possible

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```
FUNCTION GCD18(A, B)
  INTEGER*8 GCD18, A, B
  INTEGER*8 GB, T

  GCD18 = A
  GB = B

1    T = MOD(GCD18,GB)
    GCD18 = GB
    IF (T .EQ. 0) GO TO 2
    GB = T
    GO TO 1

2    CONTINUE
END

FUNCTION LCM18(A, B)
  INTEGER*8 LCM18, A, B
  INTEGER*8 GCD18
  EXTERNAL GCD18

  LCM18 = A*B/GCD18(A,B)
END
```

A Limited Language with Many Dialects



- ▶ No structured endless loops
 - ▶ Labels and **GO TO**s where used instead
- ▶ **CONTINUE** was a no-op
 - ▶ Used to mark destination of jumps
 - ▶ No comment
- ▶ **INTEGER*8** was used to declare an 8 bytes integer variable
 - ▶ Absolutely non standard
 - ▶ As are **INTEGER*1**, **INTEGER*2**, **INTEGER*4**, **REAL*4**, **REAL*8**, **COMPLEX*8**, **COMPLEX*16**
- ▶ Many dialects
 - ▶ Many proprietary extensions used to be developed
 - ▶ And then copied among vendors for compatibility reasons
 - ▶ Many extensions were eventually standardized
 - ▶ But not all of them!
 - ▶ They still lurk around, and can be tempting: resist!



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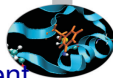
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More Types and Flow Control



- ▶ There are many integer types
 - ▶ With implementation dependent ranges
 - ▶ Selectable by kind type parameters
 - ▶ Whose limits can be devised using **huge ()** or **range ()**
- ▶ Library functions have generic names, good for most types
- ▶ And you can write your own generic interfaces
- ▶ Behavior on integer overflow is implementation defined
 - ▶ Some control is possible using parentheses
- ▶ Blocks of statements can be iterated forever...
 - ▶ ... and **exit** gets off the roundabout
- ▶ Logical conditions can be combined using **.or.** and **.and.** operators



- ▶ Do not rely on type sizes, they are implementation dependent
- ▶ Do not leave a function from inside a loop
- ▶ Think of intermediate results in expressions: they can overflow or underflow
- ▶ Be consistent with Fortran approach
 - ▶ E.g. writing generic interfaces
 - ▶ Even if it costs more work
 - ▶ Even if it costs learning more Fortran
 - ▶ Once again, you can do it in steps
 - ▶ You'll appreciate it in the future
- ▶ Hide implementation details as much as possible
 - ▶ You'll never regret
- ▶ Resist the temptation of old Fortran or non standard extensions
 - ▶ Will pay back in the future



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Compiler Errors and Warnings



- ▶ Compiler stops on errors (grammar violation, syntactic errors, ...)
- ▶ Goes on if you write non-sensical code complying with the rules!
- ▶ Compiler may perform extra checks and report warnings
 - ▶ Very useful in early development phases
 - ▶ ... sometimes pedantic
 - ▶ Read them carefully anyway



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- ▶ Goes on if you write non-sensical code complying with the rules!
- ▶ Compiler may perform extra checks and report warnings
 - ▶ Very useful in early development phases
 - ▶ ... sometimes pedantic
 - ▶ Read them carefully anyway
- ▶ **-Wall** option turns on commonly used warning on **gfortran** but not **-Wimplicit-interface** for example



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Compiler Errors and Warnings



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- ▶ **-Wall** option turns on commonly used warning on **gfortran** but not **-Wimplicit-interface** for example
- ▶ If given earlier ...
- ▶ Something is an error if not in Fortran 95 standard
 - ▶ Use **-std=f95** to force reference standard



Creating an executable from source files is in general a three phase process:

- ▶ pre-processing:
 - ▶ each source file is read by the pre-processor
 - ▶ substitute (**#define**) MACROs
 - ▶ insert code by **#include** statements
 - ▶ insert or delete code evaluating **#ifdef**, **#if** ...
- ▶ compiling:
 - ▶ each source file is translated into an object code file
 - ▶ an object code file is an organised collection of symbols, referring to variables and functions defined or used in the source file
- ▶ linking:
 - ▶ object files should be combined together to build a single executable program
 - ▶ every symbol should be resolved
 - ▶ symbols can be defined in your object files
 - ▶ or available in other object code (external libraries)

Compiling with GNU gfortran



- When you give the command:

```
user@cineca$> gfortran dsp.f90 dsp_test.f90
```



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Compiling with GNU gfortran



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user@cineca$> gfortran dsp.f90 dsp_test.f90
```

- ▶ It's like going through three steps
- ▶ Pre-processing

```
user@cineca$> gfortran -E -cpp dsp.f90  
user@cineca$> gfortran -E -cpp dsp_test.f90
```

- ▶ **-E -cpp** option, tells **gfortran** to stop after pre-process
- ▶ Simply calls **cpp** (automatically invoked if the file extension is **F90**)
- ▶ Output sent to standard output



- ▶ When you give the command:

```
user@cineca$> gfortran dsp.f90 dsp_test.f90
```

- ▶ It's like going through three steps
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user@cineca$> gfortran -E -cpp dsp.f90  
user@cineca$> gfortran -E -cpp dsp_test.f90
```

- ▶ **-E -cpp** option, tells **gfortran** to stop after pre-process
 - ▶ Simply calls **cpp** (automatically invoked if the file extension is **F90**)
 - ▶ Output sent to standard output
- ▶ Compiling sources

```
user@cineca$> gfortran -c dsp.f90  
user@cineca$> gfortran -c dsp_test.f90
```

- ▶ **-c** option tells **gfortran** to only compile the source
 - ▶ An object file **.o** is produced from each source file



- ▶ Linking object files together

```
user@cineca$> gfortran dsp.o dsp_test.o
```

- ▶ To resolve symbols defined in external libraries, specify:
 - ▶ which libraries to use (**-l** option)
 - ▶ in which directories they are (**-L** option)
- ▶ How to link the library **libdsp.a** in **/mypath**

```
user@cineca$> gfortran file1.o file2.o -L/mypath -ldsp
```

- ▶ How to create and link the DSP library:

```
user@cineca$> gfortran -c dsp.f90
ar curv libdsp.a dsp.o
ranlib libdsp.a
gfortran test_dsp.f90 -L. -ldsp
```

- ▶ **ar** create the archive **libdsp.a** containing **dsp.o**
 - ▶ **ranlib** generate index to archive
- ▶ To include file like **.mod**, specify
 - ▶ in which directories they are (**-I** option)



Introduction

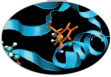
Fortran Basics

More Fortran Basics

Integer Types and Iterating

More on Compiling and Linking

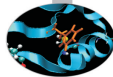
Homeworks



- ▶ Write a program that reads an integer value **limit** and prints the first **limit** prime numbers
 - ▶ Use the GCD function to identify those numbers
 - ▶ After testing the basic version, handle negative **limit** values: print an error message and attempt to read the value again



- ▶ Write a module containing a function that takes an integer **n** as input, and returns the **n-th** element of the Fibonacci series **f_n**
- ▶ Hint:
 - ▶ $F_0 = 0$
 - ▶ $F_1 = 1$
 - ▶ $F_n = F_{n-1} + F_{n-2}$
- ▶ Write a main program to test your function
 - ▶ Read **n** from standard input
 - ▶ Try with **n=2, 10, 40, 46, 48, ...**
 - ▶ What's the greatest **n := maxn**, for which **f_n** is representable by a default integer? (**huge** can help to find it out)
 - ▶ Use this information to handle too large values of **n** in your function:
 - ▶ If **n > maxn** print an error message and return -1



Part II

A Fortran Survey 2

Passing functions as arguments of procedures. Conditional and numerical loops. Managing the precision, conversions, overflow, underflow, Inf e NaN. Expressions and subexpressions with mixed types. Types, operators and logical expressions. Type character and intrinsic functions for strings. Subroutine. Array. Default constructor for arrays and implicit loops. Assumed-shape array and automatic object. Expressions with arrays and conformity.



More Flow Control
Numerical Integration
Wrapping it Up 4

Fortran Intrinsic Types, Variables and Math

Arrays



The code in this section is meant for didactical purposes only.

It is deliberately naive: focus is on language aspects, not on precision or accuracy.

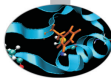
As a consequence, it is prone to numerical problems.



More Flow Control
Numerical Integration
Wrapping it Up 4

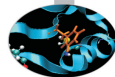
Fortran Intrinsic Types, Variables and Math

Arrays



- ▶ Let's use the trapezoidal rule to estimate $\int_a^b f(x) dx$
- ▶ Dividing the interval $[a, b]$ into n equal sized slices, it boils down to:
$$\int_a^b f(x) dx \approx \frac{b-a}{n} \left(\frac{1}{2}f(a) + \frac{1}{2}f(b) + \sum_{k=1}^{n-1} f\left(a + k\frac{b-a}{n}\right) \right)$$
- ▶ And to make it more juicy, let's make a succession of estimates, doubling n each time, until the estimate seems stable

Double Steps



```

module integrals
  implicit none
  contains
    function trap_int(a,b,f,tol)
      real :: trap_int
      real, intent(in) :: a, b, tol
      interface
        real function f(x)
          real, intent(in) :: x
        end function f
      end interface
      integer, parameter :: maxsteps = 2**23
      integer :: steps, i
      real :: acc, dx, prev_estimate, estimate

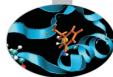
      steps = 2
      prev_estimate = 0.0 ; estimate = huge(0.0)
      dx = (b - a)*0.5
      acc = (f(a) + f(b))*0.5

conv: do while (abs(estimate - prev_estimate) > tol)
      prev_estimate = estimate
      do i=1, steps, 2
        acc = acc + f(a + i*dx)
      end do
      estimate = acc*dx
      steps = steps*2
      if (steps > maxsteps) exit conv
      dx = dx*0.5
    end do conv

      trap_int = estimate
    end function trap_int
  end module

```


Double Steps



```

module integrals
  implicit none
  contains
    function trap_int(a,b,f,tol)
      real :: trap_int
      real, intent(in) :: a, b, tol
      ! recursive approximation of integral
      ! by trapezoidal rule
      ! integration interval and tolerance
      interface
        real function f(x)
          ! function to integrate
          real, intent(in) :: x
        end function f
      end interface
      integer, parameter :: maxsteps = 2**23
      integer :: steps, i
      real :: acc, dx, prev_estimate, estimate

      steps = 2
      prev_estimate = 0.0 ; estimate = huge(0.0)
      dx = (b - a)*0.5
      acc = (f(a) + f(b))*0.5

      conv: do while (abs(estimate - prev_estimate) > tol)
        prev_estimate = estimate
        do i=1, steps, 2
          ! only contributions from new points
          acc = acc + f(a + i*dx)
        end do
        estimate = acc*dx
        steps = steps*2
        if (steps > maxsteps) exit conv
        dx = dx*0.5
      end do conv

      trap_int = estimate
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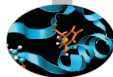
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Function Arguments



- ▶ Yes, a function can be passed as an argument to another function!
- ▶ Simply pass the name on call, like this:
`g = trap_int(-pi, pi, sinc, 0.0001)`
- ▶ And then the function can be called using the dummy argument name
- ▶ And this can be done for any procedure
- ▶ And allows for very generic code to be written
 - ▶ i.e. reuse the same routine to integrate different functions in the same program

Double Steps



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      end do
      estimate = acc*dx
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- ▶ And this can be done for any procedure
- ▶ And allows for very generic code to be written
 - ▶ i.e. reuse the same routine to integrate different functions in the same program
- ▶ Integer and real values can be mixed in expressions
 - ▶ As well as values of same type but different kind
 - ▶ And the right thing will be done
 - ▶ Which is: when two values of different type/kind meet each other at a binary operator, the one with smaller numeric range is converted to the other

Double Steps



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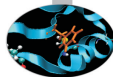
      trap_int = estimate
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```

Iterating with **do while ... end do**► **do while** (*logical-condition*)*block of statements***end do**

1. Evaluates *logical-condition*
2. If *logical-condition* is false, goes to 5
3. Executes the *block of statements*
4. Goes back to 1
5. Execution proceeds to the statement following **end do**

Double Steps



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module integrals
  implicit none
  contains
    function trap_int(a,b,f,tol)
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      if (steps > maxsteps) exit conv
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Iterating with `do while ... end do`



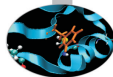
- ▶ **do while** (*logical-condition*)
block of statements
end do
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- ▶ **do** loops too can be given a name
 1. And it can be used on **exit** statements to make the flow more evident
 2. Particularly for nested loops

Iterating with `do while ... end do`



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- ▶ **do** loops too can be given a name
 1. And it can be used on **exit** statements to make the flow more evident
 2. Particularly for nested loops
- ▶ **Best practices:**
 1. use names to mark loops when they are long or belong to a deep nest
 2. NEVER, NEVER permit your code to loop forever for some inputs

Double Steps



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  implicit none
  contains
    function trap_int(a,b,f,tol)
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    end function trap_int
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```

Iterating with Counted do



```
► do var = init, limit [, step]  
    block of statements  
end do
```

Iterating with Counted do



- ▶ **do** *var* = *init*, *limit* [, *step*]
 block of statements
end do
 1. Sets *step* to 1, if none was specified

Iterating with Counted do



- **do** *var* = *init*, *limit* [, *step*]
 block of statements
end do
 1. Sets *step* to 1, if none was specified
 2. Assign the *init* value to *var*

Iterating with Counted do



► **do** *var* = *init*, *limit* [, *step*]
 block of statements
end do

1. Sets *step* to 1, if none was specified
2. Assign the *init* value to *var*
3. Evaluates $n_{iter} = \max\{0, \lfloor (limit - init + step) / step \rfloor\}$

Iterating with Counted do



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Iterating with Counted do



► **do** *var* = *init*, *limit* [, *step*]
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5. Executes n_{iter} times the *block of statements*, adding *step* to *var* at the end of each *block of statements*

Iterating with Counted do



► **do** *var* = *init*, *limit* [, *step*]
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► *var*, *init*, *limit*, and *step* should be integers

Iterating with Counted do



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- ▶ **var**, *init*, *limit*, and *step* should be integers
 - ▶ Mandatory in Fortran 2003

Iterating with Counted do

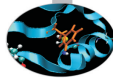


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- ▶ **var, init, limit, and step** should be integers
 - ▶ Mandatory in Fortran 2003
 - ▶ Reals can be used up to Fortran 95, but a bad idea, for both performance and reliability issues

Iterating with Counted do

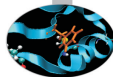


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- ▶ Less flexible than a **do while** but more efficient execution (**exit** works, anyway)



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 - ▶ Mandatory in Fortran 2003
 - ▶ Reals can be used up to Fortran 95, but a bad idea, for both performance and reliability issues
- ▶ Less flexible than a **do while** but more efficient execution (**exit** works, anyway)
- ▶ Best practice: do not give name to very tight loops

Hands-on Session #1



```

module integrals
  implicit none
  contains
    function trap_int(a,b,f,tol)
      real :: trap_int
      real, intent(in) :: a, b, tol
      interface
        real function f(x)
          real, intent(in) :: x
        end function f
      end interface
      integer, parameter :: maxsteps = 2**23
      integer :: steps, i
      real :: acc, dx, prev_estimate, estimate

      steps = 2
      prev_estimate = 0.0 ; estimate = huge(0.0)
      dx = (b - a)*0.5
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conv: do while (abs(estimate - prev_estimate) > tol)
      prev_estimate = estimate
      do i=1, steps, 2
        acc = acc + f(a + i*dx)
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```



- Write a program to exercise `trap_int()` on functions with known integrals



- ▶ Write a program to exercise `trap_int()` on functions with known integrals
- ▶ Then take care of what was left out

Time to Put it at Work



- ▶ Write a program to exercise `trap_int()` on functions with known integrals
- ▶ Then take care of what was left out
- ▶ Hints:



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- ▶ Then take care of what was left out
- ▶ Hints:
 - ▶ `trap_int()` arguments are naively handled: wrong results could be produced



- ▶ Write a program to exercise `trap_int()` on functions with known integrals
- ▶ Then take care of what was left out
- ▶ Hints:
 - ▶ `trap_int()` arguments are naively handled: wrong results could be produced
 - ▶ Robustness has been almost totally overlooked (except for the safety `exit`)



- ▶ Write a program to exercise `trap_int()` on functions with known integrals
- ▶ Then take care of what was left out
- ▶ Hints:
 - ▶ `trap_int()` arguments are naively handled: wrong results could be produced
 - ▶ Robustness has been almost totally overlooked (except for the safety `exit`)
 - ▶ What if some arguments take a **NaN** value?



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Good Ol' Fortran



- Procedure arguments and mixed-mode expressions were already there



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- ▶ Counted loops looked like this:

```
      do 10, i=1,10,3  
        write(*,*) i  
10    continue
```



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- ▶ Counted loops looked like this:

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```

- ▶ **do while, exit, end do** weren't there...
 - ▶ ... at least in the standard...
 - ▶ but are often found in codes, as dialect extensions.



More Flow Control

Numerical Integration

Wrapping it Up 4

Fortran Intrinsic Types, Variables and Math

Arrays



- ▶ More flow control
 - ▶ Procedure arguments
 - ▶ **do while**
 - ▶ Counted **do**
- ▶ Mixed-mode expressions
- ▶ Name your loops
 - ▶ Particularly if long or nested
 - ▶ Particularly if you **exit** them
 - ▶ But don't do it for short ones
- ▶ Prevent any loop from running forever for some program inputs



More Flow Control

Fortran Intrinsic Types, Variables and Math

- Integer Types

- Floating Types

- Expressions

- Arithmetic Conversions

- More Intrinsic Types

Arrays



- ▶ Computing == manipulating data and calculating results
 - ▶ Data are manipulated using internal, binary formats
 - ▶ Data are kept in memory locations and CPU registers
- ▶ Fortran doesn't make assumptions on internal data representations
 - ▶ And tries to abstract
 - ▶ Most CPU are similar but all have peculiarities
 - ▶ Some details depend on the specific executing (a.k.a. target) hardware architecture and software implementation
 - ▶ Fortran provides facilities to translate between internal formats and human readable ones
- ▶ Fortran allows programmers to:
 - ▶ think in terms of data types and named containers
 - ▶ disregard details on actual memory locations and data movements

Fortran is a Strongly Typed Language



- ▶ Each literal constant has a type
 - ▶ Dictates internal representation of the data value
- ▶ Each variable has a type
 - ▶ Dictates content internal representation and amount of memory
 - ▶ Type must be specified in a declaration before use
 - ▶ Unless you are so naive to rely on implicit declaration
- ▶ Each expression has a type
 - ▶ And subexpressions have too
 - ▶ Depends on operators and their arguments
- ▶ Each function has a type
 - ▶ That is the type of the returned value
 - ▶ Specified in function interface
- ▶ Procedure arguments have types
 - ▶ i.e. type of arguments to be passed in calls
 - ▶ Specified in procedure interface
 - ▶ If the compiler doesn't know the interface, it will blindly pass whatever you provide



More Flow Control

Fortran Intrinsic Types, Variables and Math

- Integer Types

- Floating Types

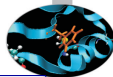
- Expressions

- Arithmetic Conversions

- More Intrinsic Types

Arrays

Integer Types (as on most CPUs)



Type	Sign	Usual huge ()	Usual Width (bits)	Usual Size (bytes)
<code>integer(selected_int_kind(2))</code>	+/-	127	8	1
<code>integer(selected_int_kind(5))</code>	+/-	32767	16	2
<code>integer</code> <code>integer(kind(0))</code> <code>integer(selected_int_kind(9))</code>	+/-	2147483647	32	4
<code>integer(selected_int_kind(18))</code>	+/-	9223372036854775807	64	8

- ▶ **`selected_int_kind(n)`** returns the least type able to host 10^n
- ▶ **`selected_int_kind(n)`** returns -1 if no suitable type is available
- ▶ New platform/compiler? Always check maximum headroom with **`huge ()`** or **`range ()`**
- ▶ As we said, on most platforms **`kind()`** returns the byte size, but it's not standard

Integer Literal Constants



- Integer literal constants have kinds too

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Integer Literal Constants



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- ▶ Unless you specify it

- ▶ In a non portable way:

`-123456_8`

- ▶ Or in a portable way:

```
integer, parameter :: i8=selected_int_kind(18)  
-123456_i8
```

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integer, parameter :: i8=selected_int_kind(18)  
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- ▶ Rule of thumb:
 - ▶ write the number as is, if it is in default integer kind range
 - ▶ otherwise, specify kind

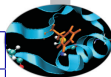
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```
- ▶ Rule of thumb:
 - ▶ write the number as is, if it is in default integer kind range
 - ▶ otherwise, specify kind
- ▶ Remember:
 - ▶ do not write `spokes = bicycles*2*36`
 - ▶ `integer, parameter :: SpokesPerWheel = 36`
 - ▶ code will be more readable, and you'll be ready for easy changes

integer Math



Function	Returns
abs (<i>i</i>)	$ i $
sign (<i>i</i> , <i>j</i>)	$ i $ if $j \geq 0$, $- i $ otherwise
dim (<i>i</i> , <i>j</i>)	if $i > j$ returns $i - j$ else returns 0
mod (<i>i</i> , <i>j</i>)	Remainder function $i - \text{int}(i/j) \times j$
modulo (<i>i</i> , <i>j</i>)	Modulo function $i - \text{floor}(i/j) \times j$
min (<i>i</i> , <i>j</i> [, ...])	$\min\{i, j [, \dots]\}$
max (<i>i</i> , <i>j</i> [, ...])	$\max\{i, j [, \dots]\}$

- ▶ Use like: **a = abs(b+i) + c**
- ▶ More functions are available to manipulate values
 - ▶ E.g. for bit manipulations on binary computers
 - ▶ We'll not cover them in this course, you can learn more about if you need to
- ▶ They can be found under different names (e.g. **iabs()**): these are relics from the past



More Flow Control

Fortran Intrinsic Types, Variables and Math

Integer Types

Floating Types

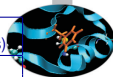
Expressions

Arithmetic Conversions

More Intrinsic Types

Arrays

Floating Types (as on most CPUs)



Type	Usual huge ()	Usual Width (bits)	Usual Size (bytes)
real real(kind(0.0)) real(selected_real_kind(6))	3.40282347e38	32	4
double precision real(kind(0.0d0)) real(selected_real_kind(15))	1.79769313486231573e308	64	8
real(selected_real_kind(18))	> 1.2e4932	80 or 128	10 or 16
complex complex(kind(0.0)) complex(selected_real_kind(6))	NA	NA	8
complex(kind(0.0d0)) complex(selected_real_kind(15))	NA	NA	16
complex(selected_real_kind(18))	NA	NA	20 or 32

- ▶ In practice, always in IEEE Standard binary format, but not a Standard requirement
 - ▶ Fortran 2008 adds the **storage_size** inquiry function
 - ▶ And some predefined kinds to represent IEEE types (**int32**, **int64**, **real32**, **real64**) using **iso_Fortran_env** module
- ▶ **selected_real_kind()** gets number of significant decimal digits, plus a second optional argument for exponent range, returns negative result if no suitable type is available
- ▶ New platform/compiler? Always check maximum headroom with **huge()** or **range()**
 - ▶ **tiny()** returns smallest positive value

real Literal Constants



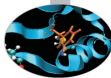
- ▶ Need something to distinguish them from integers
 - ▶ Decimal notation: `1.0`, `-17.`, `.125`, `0.22`
 - ▶ Exponential decimal notation: `2e19` (2×10^{19}), `-123.4e9` (-1.234×10^{11}), `.72e-6` (7.2×10^{-7})

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real Literal Constants



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- ▶ By default, `kind(0.0)`
- ▶ Unless you specify it
 - ▶ For double precision only:

`-1.23456d5`
 - ▶ For all kinds:

`integer, parameter :: r8=selected_real_kind(15)`

`-123456.0_r8`

real Literal Constants



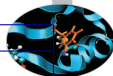
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- ▶ For all kinds:

```
integer, parameter :: r8=selected_real_kind(15)
-123456.0_r8
```

- ▶ Remember:
 - ▶ do not write `charge = protons*1.602176487E-19`
 - ▶ `real,parameter::UnitCharge=1.602176487E-19`
 - ▶ it will come handier when more precise measurements will be available



Function	Returns
abs (x)	$ x $
sign (x , y)	$ x $ if $y \geq 0$, $- x $ otherwise
dim (x , y)	if $x > y$ returns $x - y$ else returns 0
mod (x , y)	Remainder function $x - \text{int}(x/y) \times y$
modulo (x , y)	Modulo function $x - \text{floor}(x/y) \times y$
aint (x) ² , int (x) ^{1,2}	if $x > 0$ returns $\lfloor x \rfloor$ else returns $\lceil x \rceil$
anint (x) ² , nint (x) ^{1,2}	nearest integer to x
floor (x) ^{1,2} , ceiling (x) ^{1,2}	$\lfloor x \rfloor$, $\lceil x \rceil$
fraction (x)	fractional part of x
nearest (x , s)	next representable value to x , in direction given by the sign of s
spacing (x)	absolute spacing of numbers near x
max (x , y [, ...])	$\max\{x, y[, \dots]\}$
min (x , y [, ...])	$\min\{x, y[, \dots]\}$

1. Result is of integer type 2. Accept an optional argument for kind type of the result

- ▶ They can be found under different names (e.g. **dabs** ()): these are relics from the past
- ▶ More functions are available to manipulate values
 - ▶ Mostly in the spirit of IEEE Floating Point Standard
 - ▶ We'll not cover them in this course, but encourage you to learn more about



Functions	Compute
sqrt (x)	\sqrt{x}
sin (x), cos (x), tan (x), asin (x), acos (x), atan (x)	Trigonometric functions
atan2 (x, y)	Arc tangent in $(-\pi, \pi]$
exp (x), log (x), log10 (x)	e^x , $\log_e x, \log_{10} x$
sinh (x), cosh (x), tanh (x)	Hyperbolic functions

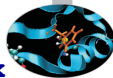
- ▶ Again, they can be found under different names (e.g. **dcos ()**): these are relics from the past



Functions	Compute
abs (z) ,	$ z $,
aimag (z)	imaginary part of z ,
real (z) ¹	real part of z
cmplx (x, y) ¹	converts from real to complex
conj (z)	Complex conjugate of z
sqrt (z)	\sqrt{z}
sin (z) , cos (z)	sine and cosine
exp (z) ,	e^z ,
log (z)	$\log_e z$
1. Accept an optional argument for kind type of the result	

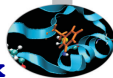
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Hands-on Session #2



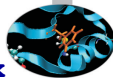
- ▶ The intrinsic function **precision (x)** for real or complex **x** returns the number of significant decimal digits.
- ▶ Write a **module** which defines the **kind** constant for single, double and quadruple real precision

Hands-on Session #2



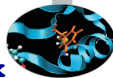
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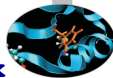


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- ▶ To gain confidence: write a small program to print out **range** and **huge** values for these kinds
- ▶ Beware:
- ▶ GNU Fortran compiler, up to release 4.5, may lack support for the quad-precision
- ▶ Check the compiler and the version you are using:
gfortran -v
- ▶ And possibly load a recent version:
module av

Let's Be *Generic*



- ▶ Use the **real_kinds** module to rewrite **dsp** module functions to support both single and double precision
- ▶ And make all of them generic procedures
- ▶ Modify your test program to see exercise the new **dsp** module



More Flow Control

Fortran Intrinsic Types, Variables and Math

Integer Types

Floating Types

Expressions

Arithmetic Conversions

More Intrinsic Types

Arrays



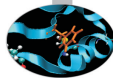
- ▶ Binary operators $+$, $-$, $*$ (multiplication) and $/$ have the usual meaning and behavior
- ▶ And so do unary operators $-$ and $+$
- ▶ Precedence
 - ▶ $-a*b + c/d$ same as $((-a)*b) + (c/d)$
 - ▶ $-a + b$ same as $(-a) + b$
- ▶ Associativity of binary ones is from left to right
 - ▶ $a + b + c$ same as $(a + b) + c$
 - ▶ $a*b/c*d$ same as $((a*b)/c)*d$
- ▶ Explicit $($ and $)$ override precedence and associativity
- ▶ $**$ is the exponentiation operator
- ▶ Assignment: $=$
 - ▶ Assigns the value of expression on right hand side to a variable on the left hand side
 - ▶ Prior to first assignment, a variable content is *undefined*



- ▶ All types are limited in range
- ▶ What about:
 - ▶ **huge** (0) + 1? (too big)
 - ▶ **-huge** (0.0) * 3.0? (too negative)
- ▶ Technically speaking, this is an arithmetic *overflow*
- ▶ And division by zero is a problem too
- ▶ For integer types, the Standard says:
 - ▶ behavior and results are unpredictable
 - ▶ i.e. up to the implementation
- ▶ For real types, it also depends on the floating point environment
 - ▶ i.e. how behavior is configured for those cases
 - ▶ you could get **-huge** (0.0) , or a **NaN**, or **-Inf**
- ▶ Best practice: NEVER rely on behaviors observed with a specific architecture and/or compiler

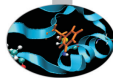
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 - ▶ As you'll remember, these are known as *side effects*



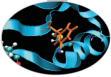
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t = foo(a, b) - bar(b, a)
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```

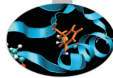
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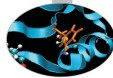
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- ▶ Ditto for order of evaluation of function arguments!
- ▶ NEVER! NEVER write code that relies on order of evaluation of subexpressions, or actual arguments!



More Flow Control

Fortran Intrinsic Types, Variables and Math

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More Intrinsic Types

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- ▶ OK when mixing integer types
 - ▶ The wider range includes the narrower one



- ▶ For the assignment statement:
 - ▶ if variable and expression have the same type, fine
 - ▶ otherwise, right operand is converted to left operand type
 - ▶ if the value cannot be represented in the destination type, it's an overflow, and you are on your own

Type Conversion Traps



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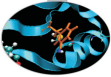
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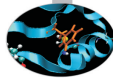
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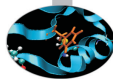
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multiplication will overflow too
 - ▶ while:
 - a = b*2_i8 + 1**
is OK

Subtle Type Conversion Traps



- Think of mixing floating and integer types

Subtle Type Conversion Traps



- ▶ Think of mixing floating and integer types
- ▶ Floating types have wider dynamic range than integer ones

Subtle Type Conversion Traps



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Subtle Type Conversion Traps



- ▶ Think of mixing floating and integer types
- ▶ Floating types have wider dynamic range than integer ones
- ▶ But not necessarily more precision
- ▶ A 32 bits **real** has fewer digits of precision than a 32 bits **integer**
- ▶ And a 64 bits **real** has fewer digits of precision than a 64 bits **integer**
- ▶ The result of a conversion could actually be smaller than expected!

Get in Control!



- Do not blindly rely on implementation dependent chance!



- ▶ Do not blindly rely on implementation dependent chance!
- ▶ Use explicit type conversion functions:
 - ▶ `int(x[, kind])`
 - ▶ `real(x[, kind])`
 - ▶ `cmplx(x[, y][, kind])`



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- ▶ Type conversion functions are not magic
 - ▶ Only convert values, not type of variables you assign to
- ▶ Do not abuse them
 - ▶ Make codes unreadable
 - ▶ Could be evidence of design mistakes
 - ▶ Or that your Fortran needs a refresh



More Flow Control

Fortran Intrinsic Types, Variables and Math

Integer Types

Floating Types

Expressions

Arithmetic Conversions

More Intrinsic Types

Arrays

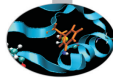
Being logical



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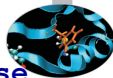


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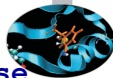
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 - ▶ or, in ancient Fortran, `.eq.`, `.ne.`, `.gt.`, `.lt.`, `.ge.`, `.le.`

- ▶ Logical expressions
 - ▶ `.not.` is unary NOT, `.and.` and `.or.` are binary AND and OR respectively, `.eqv.` is logical equivalence (`.true.` if operands both `.true.` or both `.false.`)
 - ▶ `.not. a .and. b .or. a .and. .not. b`
means

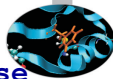
$$((.not.a) .and. b) .or. (a .and. (.not.b))$$
 - ▶ In doubt, add parentheses, but be sober



- ▶ Logical friends from `ieee_arithmetic` module (simply use it)
 - ▶ `ieee_is_finite(x): .true.` if argument value is finite
 - ▶ `ieee_is_nan(x): .true.` if argument value is NaN
 - ▶ `ieee_unordered(x, y): .true.` if at least one among `x` and `y` is NaN



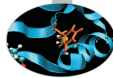
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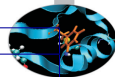
- ▶ As usual, order of subexpressions evaluation is implementation dependent

- ▶ But it's worse:
 - ▶ if `test()` is a function returning a logical type value
 - ▶ and `a` is `.true.`
 - ▶ and `b` is `.false.`
 - ▶ implementation is free (but not forced!) to not call `test()` at all in `a.or.test(x)` and `b.and.test(x)`
 - ▶ Again, do not rely on expressions side effects



- ▶ Fortran is not that good at manipulating text
- ▶ But it has some **character**:
 - ▶ **character :: c** defines a variable holding a single character, like 'f'
 - ▶ **character(len=80) :: s1, s2, s3** defines three variables holding strings of up to 80 characters, like 'Fortran 2003'
- ▶ There are character expressions, like:
 - ▶ **s3(1:40) = s1(1:20)//s2(21:40)**
 which assigns to first half of **s3** the first quarter of **s1** and second quarter of **s2**
- ▶ On assignment of a character expression to a longer variable, blank filling will take place
- ▶ On assignment of a character expression to a shorter variable, truncation will happen

String Manipulation



Function	Returns
len(s)	string length
len_trim(s)	string length with trailing blanks ignored
trim(s)	string with trailing blanks removed
repeat(s, n)	string made of n copies of s
adjustl(s)	move leading blanks to trailing position
adjustr(s)	move trailing blanks to leading position
lge(s1,s2), lgt(s1,s2), lle(s1,s2), llt(s1,s2)	string comparisons
index(s, subs)	starting position of subs in s , 0 if not found
scan(s, set)	first position in s of a character matching set , 0 if none found
verify(s, set)	first position in s of a character not matching set , 0 if all match
achar(i)	character with ASCII code i
iachar(c)	ASCII code of character c

► Our advice:

- For most practical purposes, use I/O statements to manipulate strings as internal files (more on this later)
- If you are really serious about textual data, learn more
- Or switch to a different language



More Flow Control

Fortran Intrinsic Types, Variables and Math

Arrays

Smoothing Signals

A More Compact Notation



More Flow Control

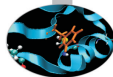
Fortran Intrinsic Types, Variables and Math

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Smoothing Signals

A More Compact Notation

In Place Smoothing of a Periodic Signal



```

module smoothing
  implicit none
  contains
    subroutine smooth(v, k)
      real,intent(inout) :: v(:)
      integer,intent(in) :: k
      integer :: n, l, i, j
      real :: work(size(v))

      n=size(v)
      l = 2*k +1
      work = 0.0
      do i=1,n
        do j=i-k,i+k
          work(i) = work(i) + v(1+mod(n-1+j, n))
        enddo
      enddo
      v = work/l
    end subroutine smooth
  end module smoothing

  program test_smooth
    use smoothing
    implicit none
    integer, parameter :: n=10
    integer :: i, k
    real :: x(n)

    k = 2
    x = (/ (real(mod(i,n/2)), i=1,n) /)
    if ( k > n) stop 'More smoothing points than array elements'
    call smooth(x,k)
    write(*,*) x
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end program test_smooth

```



- ▶ Subroutines are procedures, like functions, except they do not return any value
- ▶ They are invoked by:
`call subroutine-name(argument-list)`
- ▶ Like functions, they have *dummy* arguments that will be associated to *actual* arguments at call time
- ▶ Unlike functions, they can not be used inside expressions
- ▶ Their use is to be preferred to functions when:
 - ▶ actual arguments must be modified
 - ▶ more than one result needs to be returned

In Place Smoothing of a Periodic Signal



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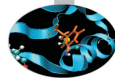
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- ▶ **real :: x(n)**
 - ▶ Declares an array named **x**
 - ▶ A collection of variables of the same type (elements), laid out contiguously in memory
 - ▶ **i**-th element can be accessed with **x(i)**
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In Place Smoothing of a Periodic Signal



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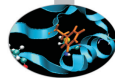
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- ▶ What's that **x = (/.../)** ?
 - ▶ **(/.../)** is an array constructor
 - ▶ i.e. a sequence of values forming an array
 - ▶ Assigned to array in a single statement
 - ▶ **(expression, index=initial, final)** evaluates **expression** for each value of **index** as in a do-loop (hence is termed *implied do-loop*)

In Place Smoothing of a Periodic Signal



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```

Subroutines and Arrays



- ▶ Arrays can be passed as arguments to procedures
- ▶ How can subroutine *smooth* know the size of the actual argument passed as **v**?
 - ▶ **real :: v(:)** states that size of **v** will be that of the actual argument
 - ▶ **v** is termed an *assumed-shape* array
 - ▶ This only works if the subroutine has explicit interface
- ▶ Otherwise, you can still use the good ol' way:

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subroutine smooth(v,k,n)
  integer n
  real v(n)
  ...
```

In Place Smoothing of a Periodic Signal



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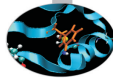
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    call smooth(x,k)
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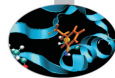
```

subroutine smooth(v,k,n)
  integer n
  real v(n)
  ...

```

- ▶ How can subroutine *smooth* declare a local array matching in size the actual argument?
 - ▶ **size(v)** returns the number of elements (size) of **v**
 - ▶ **real :: work(size(v))** gives **work** same size as **v**
 - ▶ **work** is termed an *automatic object*

WARNING: NO BOUNDS CHECKING!



- In Fortran, there is no bounds checking on array access
- And it is possible for something like this to happen

```
real :: a(10)
...
do i=-100,100
  a(i) = i
end do
```

- If you are lucky, you'll get a runtime error, otherwise you'll corrupt surrounding memory areas, with really puzzling behavior
- Once upon a long ago, it used to be a 'feature':

```
subroutine smooth(v,k,n)
  integer n
  real v(1)
  ...
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  real v(1)
  ...
```

- ▶ Use compiler options to enable runtime detection of out of bounds accesses
 - ▶ But execution is incredibly slowed down
 - ▶ Just a debugging tool, do not use it in production



- The intrinsic subroutine `cpu_time()` is used to time code regions

```
real :: t1, t2
...
call cpu_time(t1)
...           ! code to be timed
call cpu_time(t2)
write(*,*) 'Execution time for section 1: ', t2-t1, 'seconds'
```



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- ▶ Takes a default real argument
- ▶ And returns in it processor time consumed by the program in seconds



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```

- ▶ Takes a default real argument
 - ▶ And returns in it processor time consumed by the program in seconds
- ▶ Use it to measure execution time of **test_smooth** program
- ▶ Can we use less operations to get the same results (within round-off errors)?



More Flow Control

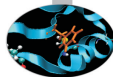
Fortran Intrinsic Types, Variables and Math

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A More Compact Notation

Same Smoothing in a Different Idiom



```

module smoothing
  implicit none
contains

  subroutine smoothinplace(v, k)
    implicit none
    real,intent(inout) :: v(:)
    integer,intent(in) :: k
    real :: work(-k+1:size(v)+k)
    integer :: i, j, l, n

    n=size(v)
    l = 2*k + 1
    work(1:n) = v
    work(-k+1:0) = v(n-k+1:n)
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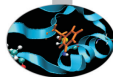
    do j=1, k
      v = v + work(1-j:n-j) + work(1+j:n+j)
    end do
    v = v/l

  end subroutine smoothinplace

end module smoothing

```

Same Smoothing in a Different Idiom



```

module smoothing
  implicit none
  contains

  subroutine smoothinplace(v, k)
    implicit none
    real,intent(inout) :: v(:)
    integer,intent(in) :: k
    real :: work(-k+1:size(v)+k)
    integer :: i, j, l, n

    n=size(v)
    l = 2*k +1
    work(1:n) = v
    work(-k+1:0) = v(n-k+1:n)
    work(n+1:n+k) = v(1:k)

    do j=1, k
      v = v + work(1-j:n-j) + work(1+j:n+j)
    end do
    v = v/l

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```




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Array Slices



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work(-k+1:size(v)+k)

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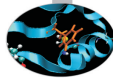
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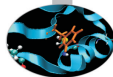


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work(n+1:n+k) selects...
- ▶ Arrays and array sections are assigned to by = in a natural manner (more on this later)

Same Smoothing in a Different Idiom



```

module smoothing
  implicit none
contains

  subroutine smoothinplace(v, k)
    implicit none
    real,intent(inout) :: v(:)
    integer,intent(in)  :: k
    real                :: work(-k+1:size(v)+k)
    integer :: i, j, l, n

    n=size(v)
    l = 2*k + 1
    work(1:n) = v
    work(-k+1:0) = v(n-k+1:n)
    work(n+1:n+k) = v(1:k)

    do j=1, k
      v = v + work(1-j:n-j) + work(1+j:n+j)
    end do
    v = v/l

  end subroutine smoothinplace

end module smoothing

```



- ▶ Arrays and array sections may be
 - ▶ referenced and used in expressions
 - ▶ passed as arguments to procedures

```
do j=1, k
  v = v + work(1-j:n-j) + work(1+j:n+j)
end do
```

- ▶ Without array expressions, this code would look like:

```
do j=1, k
  do i=1, n
    v(i) = v(i) + work(i-j) + work(i+j)
  end do
end do
```

- ▶ In an array expression, result must not depend in any way on the order of evaluation of elements
- ▶ You should think of array expressions as if all elements were computed at the same time



- ▶ The size of a one-dimensional array is its *shape*
- ▶ Arithmetic operators act on arrays element by element
- ▶ Binary operators combine pairs of corresponding elements from the operands
- ▶ With binary operators and assignments, you must use *conformable*, i.e. identically shaped, arrays
- ▶ Except for scalar values (not variables!), that match any shape, as if they were replicated

```

real, dimension(4) :: u, v, w
real :: t(1), s
t = s ! it's right
s = t ! it's wrong
w = (u-v)**2 ! it's right
w = s*u+v+2.3 ! it's OK
w = u+v(1:2) ! it's wrong
  
```

- ▶ By the way, **dimension** attribute lets you specify bounds and dimensions for a list of identical arrays



- ▶ Intrinsic subroutine **random_number (x)** returns pseudo-random numbers uniformly distributed in $[0, 1)$ interval
 - ▶ Takes an argument of type **real**, that can be either a scalar or an array
 - ▶ Returns one random number if **x** is a scalar
 - ▶ Returns an array of random numbers if **x** is an array
- ▶ Is **random_number ()** as uniform as advertised? Let's check...

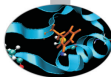
Let's Build An Histogram



- ▶ Write a program that:
 1. reads an integer **niter** from standard input
 2. generates **niter** random numbers in interval [0, 10)
 3. builds an histogram and computes their average
 4. Prints out results

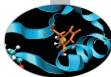
- ▶ To build the histogram:
 1. Initialize to 0s an array **hist** of 20 **integers** to hold the bin count, then, at each iteration:
 2. generate a random number
 3. find out the bin it belongs to (i.e. its index in the array **hist**)
 4. intrinsic **ceiling(x)** function helps: it returns $\lceil x \rceil$
 5. increment the corresponding array element and compute the percentages
 6. accumulate the sum of the random numbers to compute the average value

Hands-on Session #5



- ▶ A prime number is a natural number which has only two distinct natural divisors: 1 and itself
- ▶ Find all primes less than or equal to a given n by Eratosthenes' algorithm:
 1. create a list of consecutive integers from 2 to n
 2. let be $p \leftarrow 2$ the first prime
 3. strike from the list all multiples of p up to n
 4. let $p \leftarrow$ next number still in the list after p
 5. if $2p < n$, get back to step 3
 6. all remaining numbers in the list are primes

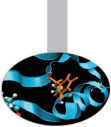
Try it now!



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Try it now!

- ▶ How could you spare iterations?
- ▶ How could you spare memory?



Part III

Array Syntax and I/O

Multidimensional arrays, array-syntax, array-value function, temporary array, shape, data, reshape, constant array and elemental procedure. Coconstructs where, forall, array reduction. Advanced I/O: formats and descriptors, I/O to/from file, namelist, internal file, unformatted I/O, positioning instructions, stream access. Managing errors.



Array Syntax

- More dimensions

- Not a Panacea

- Arrays of Constants

- Elemental Procedures

- More Array Syntax

Input/Output



Array Syntax

- More dimensions

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- Input/Output

Matrix Averaging



```
function avgk(v, k)

    implicit none

    real,intent(in) :: v(:, :)
    integer,intent(in) :: k
    real :: avgk(size(v,1)/k,size(v,2)/k)

    integer :: i, j, n, m

    n = (size(v,1)/k)*k
    m = (size(v,2)/k)*k

    avgk = 0.0

    do j=1, k
        do i=1, k
            avgk = avgk + v(i:n:k,j:m:k)
        end do
    end do

    avgk = avgk/k**2

end function avgk
```

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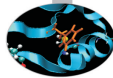
  avgk = avgk/k**2

end function avgk
  
```



- ▶ Arrays may have up to 7 dimensions
- ▶ Lower bounds default to 1, but you can specify them as for one-dimensional arrays, like in `q(-k:k, 11:20)`
- ▶ Elements are referenced by a list of indices: `v(1, 1)`
- ▶ The sequence of extents of an array is termed its *shape*, e.g. if `a` is `real :: a(3, 2:5)` then:
 - ▶ `shape(a)` returns the array of extents `(/3, 4/)`
 - ▶ whereas `size(a)` returns `12`
- ▶ Multidimensional (i.e. `rank>1`) arrays and array sections may be involved in array expressions
- ▶ As in the case of rank 1 arrays, they must be conformable when needed:
`avgk(1:3, :) = avgk(5:9, :)` is wrong

Arrays and memory



- Some statements treat the elements of an array one by one in a special order, the *array element order*
 - obtained by counting most rapidly in the early dimensions
 - in the natural matrix representation this corresponds to storing the elements by column

a(1,1)	a(1,2)	a(1,3)	a(1,4)
a(2,1)	a(2,2)	a(2,3)	a(2,4)
a(3,1)	a(3,2)	a(3,3)	a(3,4)

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)
--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------

- Most implementations actually store arrays in contiguous storage following the array element order
 - not required by the Standard, though
 - but crucial wrt performances, a typical optimization topic
- When dealing with complex data structures, the contiguity issue arises
 - Fortran 2008 adds the **contiguous** keyword to somehow address it

Matrix Averaging



```

function avgk(v, k)

  implicit none

  real,intent(in) :: v(:, :)
  integer,intent(in) :: k
  real :: avgk(size(v,1)/k,size(v,2)/k)

  integer :: i, j, n, m

  n = (size(v,1)/k)*k
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  avgk = 0.0

  do j=1, k
    do i=1, k
      avgk = avgk + v(i:n:k,j:m:k)
    end do
  end do

  avgk = avgk/k**2

end function avgk
  
```


Array-Valued Functions

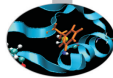


- ▶ Yes, a function may return an array
 - ▶ And can be used in array expressions
 - ▶ Its type is defined like any automatic object
 - ▶ It must be assigned values inside the function
 - ▶ No array-sections of the result can be selected on invocation



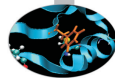
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Matrix Averaging



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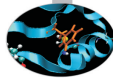
    n = (size(v,1)/k)*k
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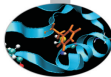
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- ▶ An explicit interface is mandatory in the calling program
- ▶ **`size(array, dim)`** returns the integer extent of **`array`** along dimension **`dim`**
- ▶ Number of dimensions (a.k.a. rank) is mandatory in assumed shape arrays

Pay Attention to Conformability



- Readability of array syntax may become questionable...
Try to translate the previous code without using array syntax

Matrix Averaging



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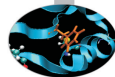
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    ! do i=1, k
    !   do x=1, size(avgk,1)
    !   do y=1, size(avgk,2)
    !       avgk(x,y) = avgk(x,y) + v(i+(x-1)*k,j+(y-1)*k)
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    ! end do
    ! end do

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end function avgk
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Matrix Averaging



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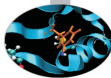
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    ! end do

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- Why are **n** and **m** computed that way?

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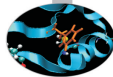
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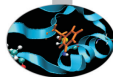
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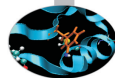
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 - ▶ Runtime checking is too costly for a performance oriented language
 - ▶ And out of bounds access could happen
- ▶ Compile time detection of non conformable operands only works in a few cases
- ▶ Again, use compiler options for runtime bounds checking

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- ▶ what if **v** extents aren't multiple of **k**?
 - ▶ **v(i:n:k, j:m:k)** and **avgk** would not be conformable
 - ▶ This cannot be checked at compile time, when shape of **v** and value of **k** are still unknown
 - ▶ Runtime checking is too costly for a performance oriented language
 - ▶ And out of bounds access could happen
- ▶ Compile time detection of non conformable operands only works in a few cases
- ▶ Again, use compiler options for runtime bounds checking
- ▶ Again, very slow, only tolerable in debugging

Lower-Triangular Linear System



► Good ol' style:

```
do i=1,n
  x(i) = b(i) / a(i,i)
  do j=i+1,n
    b(j) = b(j) - A(j,i)*x(i)
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► In modern idiom:

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► What happens for $i==n$?

Lower-Triangular Linear System



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```

► What happens for $i==n$?

- the array section $b(n+1:n)$ has zero size:
lower bound > upper bound
- No operation is performed

Picking Up Array Elements



- `a(11:20)` specifies all elements from index 11 to index 20

Picking Up Array Elements



- ▶ **a(11:20)** specifies all elements from index 11 to index 20
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Picking Up Array Elements



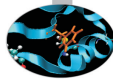
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Picking Up Array Elements



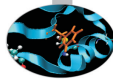
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Picking Up Array Elements

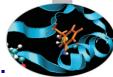


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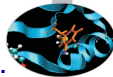
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 - ▶ **`size(shape(b))`** returns 1
 - ▶ and **`size(b)`** returns 10

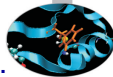


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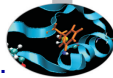
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A Closer Look To Array Expressions



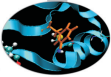
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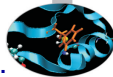
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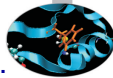


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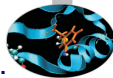
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- ▶ Array syntax can be very compact and elegant
- ▶ But temporary copies may impact performance, use your compiler options to spot them



Array Syntax

More dimensions

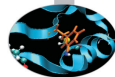
Not a Panacea

Arrays of Constants

Elemental Procedures

More Array Syntax

Input/Output



```
function trace(matrix)
implicit none
real, intent(in) :: matrix(:, :)
real :: trace
integer :: i
integer :: dim(2)

dim = shape(matrix)
trace = 0.0
if (dim(1) /= dim(2)) return

do i=1,dim(1)
    trace = trace + matrix(i,i)
enddo
end function trace
```

- ▶ Not all operations on arrays can easily be expressed in array syntax
- ▶ Do you remember **shape()**? It returns an array whose elements are the extents of its argument

Optimized Array Smoothing



```
subroutine smooth(v, k)
  implicit none
  real,intent(inout) :: v(:)
  integer,intent(in) :: k
  integer :: n, l, i, j
  real :: work(size(v))

  n=size(v)
  l = 2*k +1
  work(1) = 0.0
  do j=1-k,1+k
    work(1) = work(1) + v(1+mod(n-1+j, n))
  enddo
  do i=2,n
    work(i)=work(i-1)+v(1+mod(n-1+i+k, n))-v(1+mod(n-2+i-k, n))
  enddo
  v = work/l
end subroutine smooth
```

- ▶ The above code does the smoothing with minimal operations count
- ▶ And cannot be expressed at all in array syntax
- ▶ This is a quite common situation: optimal algorithms operating on arrays often sport dependencies in elements evaluations and updates



Array Syntax

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! Polynomial approximation of $J_0(x)$ for $-3 \leq x \leq 3$
 ! See Abramowitz&Stegun for details

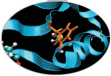
```

function j0(x)
  implicit none
  real :: j0
  real, intent(in) :: x

  integer, parameter :: order = 6
  real, parameter, dimension(0:order) :: coeff = &
    (/ 1.0000000, &
      -2.2499997, &
      1.2656208, &
      -0.3163866, &
      0.0444479, &
      -0.0039444, &
      0.0002100 /)
  real :: xo3sq
  integer :: i

  xo3sq = (x/3.0)**2
  j0 = coeff(order)

  ! horner method
  do i=order, 1, -1
    j0 = j0*xo3sq + coeff(i-1)
  end do
end function j0
  
```



- ▶ **parameter** arrays are very good at storing tables of:
 - ▶ polynomial coefficients
 - ▶ physical measurements
 - ▶ function values at discrete points
- ▶ In the past, **data** statements were used:

```
data coeff /1.0,-2.2499997,1.2656208,-0.3163866, &  
          0.0444479,-0.0039444,0.0002100/
```
- ▶ **data** statements:
 - ▶ are very versatile
 - ▶ very difficult to decipher
 - ▶ and tend to float away from variable declaration
- ▶ Use initialization instead



Array Syntax

More dimensions

Not a Panacea

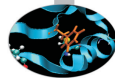
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Input/Output

Arrays Swap



```
program array_swap

  implicit none
  integer :: i, j
  real    :: a(0:10,10), b(11,10)


  a=reshape( (/ (i*0.1, i=1,110) /), (/11,10/) )
  b=reshape( (/ ((i*j+i, i=1,11), j=1,10) /), (/11,10/) )
  call swap(a,b)

end program array_swap


subroutine swap(a,b)

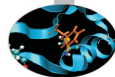
  implicit none

  real, intent(inout) :: a(:,:),b(:,:)
  real, dimension(size(a,1),size(a,2)) :: tmp

  tmp = a
  a = b
  b = tmp

end subroutine swap
```

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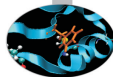
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- ▶ **reshape** (*source*, *new_shape*) returns an array with shape given by the rank one integer array *new_shape*, and elements taken from *source* in array element order

Arrays Swap



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program array_swap

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  interface
    subroutine swap(a,b)
      real, intent(inout)      :: a(:, :), b(:, :)
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    end subroutine swap
  end interface

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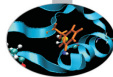
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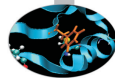


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- ▶ But life can be simpler...

Elemental Arrays Swap



```

program array_swap
  implicit none
  integer :: i, j
  real    :: a(0:10,10), b(11,10)

  interface
    elemental subroutine swap(a,b)
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      real                :: tmp
    end subroutine swap
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 - ▶ If a subroutine, side effects shall be restricted to **intent (out)** and **intent (inout)** arguments
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 - ▶ Of course, a procedure that appears to be pure, but calls a non pure procedure, is not pure at all!
 - ▶ And some more constraints ensure the different procedure calls can be safely executed in any order
- ▶ An explicit interface is mandatory
 - ▶ It must specify the procedure as **elemental**
 - ▶ It must specify **intent ()** attribute for all arguments



Array Syntax

More dimensions

Not a Panacea

Arrays of Constants

Elemental Procedures

More Array Syntax

Input/Output

Masks and **where**



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- ▶ Pay attention if you use non elemental functions in a **where**, you could be in for a surprise!



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- ▶ Pay attention if you use non elemental functions in a **where**, you could be in for a surprise!
- ▶ **where** constructs can be nested and given a name

Say it With **forall**s



- **forall** allows writing array assignments which cannot be expressed with array expressions:

```
forall(i = 1:n) a(i,i) = x(i)**2
```

Say it With **forall**s



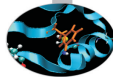
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  b(i,j) = a(i,j)
end forall
```

It works like array assignments:

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It works like array assignments:

- ▶ Unlike **do**, there is no ordering of iterations, and changes appear as they were deferred
- ▶ Thus, no conflicts between reads and writes to **a**

Say it With **forall**s



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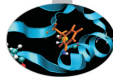
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- ▶ **forall** constructs can be nested and given a name

Laplace Equation in Three Idioms



- Using **do** loops (dependencies! loop order is crucial)

```
do j=2,n-1
  do i=2,n-1
    T(i,j) = ( T(i-1,j) + T(i+1,j) + &
               T(i,j-1) + T(i,j+1) )/4.0
  enddo
enddo
```

Laplace Equation in Three Idioms

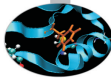


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```
do j=2,n-1
  do i=2,n-1
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               T(i,j-1) + T(i,j+1) )/4.0
  enddo
enddo
```

- Using array syntax (compiler enforces correct semantics)

```
T(2:n-1,2:n-1) = ( T(1:n-2,2:n-1) + T(3:n,2:n-1) &
                   + T(2:n-1,1:n-2) + T(2:n-1,3:n) )/4.0
```



- Using **do** loops (dependencies! loop order is crucial)

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do j=2,n-1
  do i=2,n-1
    T(i,j) = ( T(i-1,j) + T(i+1,j) + &
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  enddo
enddo
  
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- Using array syntax (compiler enforces correct semantics)

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                   + T(2:n-1,1:n-2) + T(2:n-1,3:n) )/4.0
  
```

- Using **forall** (ditto, but more readable)

```

forall (i=2:n-1, j=2:n-1)
  T(i,j) = ( T(i-1,j) + T(i+1,j) + &
             T(i,j-1) + T(i,j+1) )/4.0
end forall
  
```

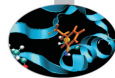
Bilateral Filter Using forall



```

integer, parameter :: maxn=768, maxm=939, R=3
real, parameter :: sd=10.0, sr=10.0
real, parameter :: sd22=2.0*sd**2, sr22=2.0*sr**2
integer :: i,j,m,n
real :: B(maxn,maxm), A(maxn,maxm)
real :: z(-R:R,-R:R), aw(-R:R,-R:R)
real, dimension(-R:R,-R:R), parameter :: z0=&
  reshape((/ ((exp(-(m**2 + n**2)/sr22), m=-R, R), n=-R,R) /), (/ 2*R+1, 2*R+1 /))
...
do i=1,maxn      ! These two cannot be changed into forall
  do j=1,maxm    ! Why?
    z = 0.0
    forall (m=max(1,i-R):min(maxn,i+R))
      forall (n=max(1,j-R):min(maxm,j+R))
        aw(m-i,n-j) = A(m,n)
        z(m-i,n-j) = exp(-(aw(m-i,n-j)-A(i,j))**2/sd22)*z0(m-i,n-j)
      end forall
    end forall
    B(i,j) = sum(z*aw)/sum(z)
  end do
end do
  
```

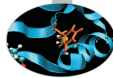
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integer :: i,j,m,n
real :: B(maxn,maxm), A(maxn,maxm)
real :: z(-R:R,-R:R), aw(-R:R,-R:R)
real, dimension(-R:R,-R:R), parameter :: z0=&
    reshape((/ ((exp(-(m**2 + n**2)/sr22), m=-R, R), n=-R,R) /), (/ 2*R+1, 2*R+1 /))
...
do i=1,maxn      ! These two cannot be changed into forall
do j=1,maxm      ! Why?
    z = 0.0      ! Because this happens at every iteration, it's a dependency!
    forall (m=max(1,i-R):min(maxn,i+R))
        forall (n=max(1,j-R):min(maxm,j+R))
            aw(m-i,n-j) = A(m,n)
            z(m-i,n-j) = exp(-(aw(m-i,n-j)-A(i,j))**2/sd22)*z0(m-i,n-j)
        end forall
    end forall
    B(i,j) = sum(z*aw)/sum(z)
end do
end do

```

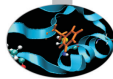


- ▶ Reductions squeeze an array to a scalar
 - ▶ **all(*mask*)** returns true if all the elements of mask are true
 - ▶ **any(*mask*)** returns true if any of the elements of mask are true
 - ▶ **count(*mask*)** returns the number of **.true.** elements in mask
 - ▶ **maxval(*array*)** returns the maximum value of array
 - ▶ **minval(*array*)** returns the minimum value of array
 - ▶ **sum(*array*)** returns the sum of the elements of array
 - ▶ **product(*array*)** returns the product of the elements of array
- ▶ Or to an array of rank reduced by one, if you specify an optional dimension to perform reduction along, like in
sum(a(:, :, :), dim=2)

More Array Little Helpers



- ▶ More functions, good to know:
 - ▶ **maxloc()** and **minloc()** return locations of maximum and minimum value respectively
 - ▶ **cshift()** performs a *circular* shift along an array dimension
 - ▶ **eoshift()** perform a *end-off* shift along an array dimension
 - ▶ **spread()** increases by one the rank of an array expression
 - ▶ **pack()** selects elements from an array according to a mask and packs them in a rank-1 array
 - ▶ And **unpack()** does the reverse
- ▶ But too much detail to cover in this introduction, look for them on your compiler documentation, and experiment



- ▶ Vector and matrix multiplication functions
 - ▶ `dot_product(vector_a, vector_b)`
 - ▶ `matmul(matrix_a, matrix_b)`
- ▶ But the BLAS libraries are around
 - ▶ Widely used
 - ▶ Highly optimized implementations available
- ▶ Outstanding compilers include special purpose, optimized BLAS version for those calls
- ▶ Good compilers do not include BLAS, but give option to link them for those calls
- ▶ Average compilers do not shine for those calls
- ▶ Our advice: install a reputedly good BLAS version and use it
- ▶ There is more to matrix algebra than matrix multiplies and vector products



- Re-write the Sieve of Eratosthenes algorithm using array syntax



Array Syntax

Input/Output

- Formatted I/O

- File I/O

- Namelist

- Internal Files

- Unformatted I/O

- Robust I/O



Array Syntax

Input/Output

Formatted I/O

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Internal Files

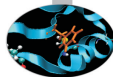
Unformatted I/O

Robust I/O



- ▶ Data are manipulated in internal (usually binary) format
- ▶ Fortran Standard leaves internal format details up to the implementation
- ▶ Formatted I/O translates internal representation of variables into human readable format
- ▶ Best practices:
 - ▶ Use formatted I/O just for small amount of data meant to be read by humans
 - ▶ Beware: human readable representation may cause problems because of rounding or not enough digits
 - ▶ Do not use I/O inside heavy computations: inhibits some code optimizations, and significantly affects performance

Iterative search for the Golden Ratio



```

program golden_ratio
! experiments with the golden ratio iterative relation
implicit none
integer, parameter :: rk = kind(1.0d0)
real(rk) :: phi, phi_old
real(rk) :: phi_start, tol
integer :: i, max_iter

write(*,*) 'Enter start value, tol, max iterations'
read(*,*) phi_start, tol, max_iter

phi_old = phi_start
do i=1,max_iter
    phi = 1.0d0/phi_old + 1.0d0
    if (abs(phi - phi_old) < tol) exit
    phi_old = phi
end do

write(*,100) 'Start value:',phi_start
write(*,100) 'Tolerance:',tol
write(*,'(2(A," ",I11," "))') 'Ended at iteration:', i, 'of', max_iter
write(*,100) 'Final value:',phi

100 format(A," ",F13.10)
end program golden_ratio
    
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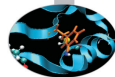



- ▶ The easiest way to do formatted I/O
- ▶ Specified using `*`
- ▶ Values are translated according to their types
- ▶ In the order they are listed on I/O statements
- ▶ No-nonsense, implementation dependent format
- ▶ Often outputs more digits than you actually care of
- ▶ Best practices:
 - ▶ Use it for terminal input
 - ▶ Use it for input of white-space separated values
 - ▶ Use it for quick output
 - ▶ Not suitable for rigid tabular formats



- Put you in total control of what is read/written

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Explicit **formats**



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- Specified by (***format-list***)

Explicit **formats**



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- ▶ Where ***format-list*** is a comma separated list of items, which can be:
 - ▶ string literals, usually in double quotes, emitted *as-is*
 - ▶ or proper *edit descriptors*, which dictate how a corresponding element on the I/O list should be converted



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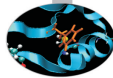
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phi_old = phi_start
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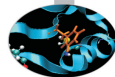
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- ▶ *Repeat counts* can be used
 - ▶ Like in **5I3**, which will convert 5 **integer** values
 - ▶ Like in **2 (I3,F7.4)**, which will convert 2 pairs, each made of an **integer** and a **real** value

Iterative search for the Golden Ratio



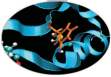
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read(*,*) phi_start, tol, max_iter

phi_old = phi_start
do i=1,max_iter
    phi = 1.0d0/phi_old + 1.0d0
    if (abs(phi - phi_old) < tol) exit
    phi_old = phi
end do

write(*,100) 'Start value:',phi_start
write(*,100) 'Tolerance:',tol
write(*,'(2(A," ",I11," "))') 'Ended at iteration:', i, 'of', max_iter
write(*,100) 'Final value:',phi

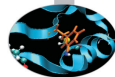
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end program golden_ratio
```

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 - ▶ Like in **2 (I3,F7.4)**, which will convert 2 pairs, each made of an **integer** and a **real** value
- ▶ Formats must be specified on I/O statements
 - ▶ As a literal string, usually in single quotes
 - ▶ As a character expression
 - ▶ As a numeric label of a **format** statement in the same program unit (traditionally, before its end), reusable in many statements



- ▶ **A** is used to translate **character** values
 - ▶ **A** will emit the value as is
 - ▶ **A10** will emit 10 characters, truncating the value if longer, right justifying it if shorter
 - ▶ Beware: leading white-space skipped on input
 - ▶ Beware: **A10** and **10A** mean very different things!



- ▶ **A** is used to translate **character** values
 - ▶ **A** will emit the value as is
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- ▶ **I** is used to translate **integer** values
 - ▶ **I6** will emit up to 6 characters (sign included!), right justified with blanks
 - ▶ **I6.3** will emit 6 characters (sign included!), containing at least 3 (possibly zero) digits, right justified with blanks
 - ▶ Beware: again, **I10** and **10I** mean very different things!

Edit Descriptors: `real`s



- ▶ **F** can be used to translate `real` values
 - ▶ **F8.3** will emit up to 8 characters (sign and decimal point included!) in total, with 3 decimal digits (possibly zero), right justified with blanks
 - ▶ Beware: if **F6.2** is specified in input, and `-12345` is met, the value `-123.45` will be read in!
 - ▶ Beware: if **F6.2** is specified in input, and `-1.234` is met, the value `-1.234` will be read in anyhow!
- ▶ Beware of rounding: internal representation could have more precision than specified in edit descriptors

More Edit Descriptors for `real`s



- ▶ **E** (or **D**) can also be used to translate `real` values
 - ▶ Exponential form is used (mantissa in the $[0,1)$ range)
 - ▶ Values $|x| < 10^{99}$, as -1.5372×10^{98} , will be converted like:
-.15372E+99
 - ▶ Values $|x| \geq 10^{99}$, as -1.5372×10^{99} , will be converted like:
-.15372+100
 - ▶ **E15.7** will emit up to 15 characters (sign, decimal point, and exponent field included!), with 7 decimal mantissa digits (possibly zero), right justified with blanks
 - ▶ Ditto for **E15.7E4**, except that 4 digits will be used for exponent
 - ▶ Again, input is more liberal

More Edit Descriptors for `real`s



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-.15372+100
 - ▶ **E15.7** will emit up to 15 characters (sign, decimal point, and exponent field included!), with 7 decimal mantissa digits (possibly zero), right justified with blanks
 - ▶ Ditto for **E15.7E4**, except that 4 digits will be used for exponent
 - ▶ Again, input is more liberal
- ▶ And more can be used to the same purpose
 - ▶ Like **EN** (engineering notation), same as **E**, with exponent always multiple of 3
 - ▶ Like **G**, which uses the most suitable between **F** and **E**, depending on the value magnitude

Even More Edit Descriptors



- ▶ /
 - ▶ Forces a new line on output
 - ▶ Skips to next line on input



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- ▶ Leading sign of numeric values
 - ▶ **SP** forces following numeric conversions to emit a leading + character for positive values
 - ▶ **SS** restores the default (sign is suppressed for positive values)



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- ▶ Embedded blanks in numeric input fields
 - ▶ **BZ** forces embedded blanks to be treated as 0 digits
 - ▶ **BN** restores the default (blanks are skipped)



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 - ▶ Forces a new line on output
 - ▶ Skips to next line on input

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- ▶ Embedded blanks in numeric input fields
 - ▶ **BZ** forces embedded blanks to be treated as 0 digits
 - ▶ **BN** restores the default (blanks are skipped)

- ▶ And more... browse your compiler manuals

complexes and Arrays



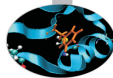
- ▶ **complex** values are made of two reals
 - ▶ Thus two edit descriptors must be provided
 - ▶ First one for real part, second one for imaginary part



- ▶ **complex** values are made of two reals
 - ▶ Thus two edit descriptors must be provided
 - ▶ First one for real part, second one for imaginary part
- ▶ Arrays are indexed collections of elements
 - ▶ Thus a proper edit descriptor must be provided for each element
 - ▶ And if elements are of **complex**, or derived types, see above

Fortran I/O is Robustly Designed

- What if more characters than needed are present on an input line?



Fortran I/O is Robustly Designed



- ▶ What if more characters than needed are present on an input line?
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Fortran I/O is Robustly Designed



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- ▶ What if the list of items to read/write is exhausted before end of edit descriptors in a format?

Fortran I/O is Robustly Designed



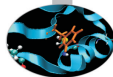
- ▶ What if more characters than needed are present on an input line?
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- ▶ What if the list of edit descriptors in a format is exhausted before end of items to read/write?

Iterative Matrix Inversion



```

program iterative_inversion
! experiments with matrix iterative inversion
implicit none
real, dimension(4,4) :: a, x, x_old, x_start
real :: tol, err
integer :: i, max_iter

write(*,*) 'Enter 4x4 matrix to invert'
read(*,*) a
write(*,*) 'Enter 4x4 start matrix'
read(*,*) x_start
write(*,*) 'Enter tol, max iterations'
read(*,*) tol, max_iter

x_old = x_start
do i=1,max_iter
    x = 2.0*x_old - matmul(x_old,matmul(a,x_old))
    err = maxval(abs(x - x_old))
    if (err < tol) exit
    x_old = x
end do

write(*,(' ("Matrix to invert:")'))
write(*,100) a
write(*,(' (/,"Start matrix:")'))
write(*,100) x_start
write(*,(' (/,"A," ",E15.7')) 'Tolerance:',tol
write(*,(' (/,"2(A," ",I11," ")')) 'Ended at iteration:', i, 'of', max_iter
write(*,(' ("Final matrix:")'))
write(*,100) x

100 format(4(E15.7," "))
end program iterative_inversion

```

Fortran I/O is Robustly Designed



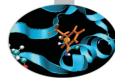
- ▶ What if more characters than needed are present on an input line?
 - ▶ After **read**, remaining ones are ignored up to end of line
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 - ▶ Following edit descriptors are ignored
- ▶ What if the list of edit descriptors in a format is exhausted before end of items to read/write?
 - ▶ Easy answer: I/O continues on a new line, reapplying the format list from its beginning, quite handy for arrays

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 - ▶ Could be more complex, look for *reversion* to know more

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- ▶ What if a numeric value is too big to fit the characters you specified on its corresponding edit descriptor?

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- ▶ What if a type mismatch happens between an item to read/write and its corresponding edit descriptor?
 - ▶ Your fault, you are in for a runtime, implementation defined surprise!



Array Syntax

Input/Output

Formatted I/O

File I/O

Namelist

Internal Files

Unformatted I/O

Robust I/O

Iterative search for the Golden Ratio



```

program golden_ratio
! experiments with the golden ratio iterative relation
implicit none
integer, parameter :: rk = kind(1.0d0)
real(rk) :: phi, phi_old
real(rk) :: phi_start, tol
integer :: i, max_iter

open(11,FILE='golden.in',STATUS='old')
read(11,*) phi_start, tol, max_iter
close(11)

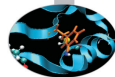
phi_old = phi_start
do i=1,max_iter
    phi = 1.0d0/phi_old + 1.0d0
    if (abs(phi - phi_old) < tol) exit
    phi_old = phi
end do

open(12,FILE='golden.out')
write(12,100) 'Start value:',phi_start
write(12,100) 'Tolerance:',tol
write(12,'(2(A," ",I11," "))') 'Ended at iteration:', i, 'of', max_iter
write(12,100) 'Final value:',phi
close(12)

100 format(A," ",F13.10)
end program golden_ratio

```

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integer, parameter :: rk = kind(1.0d0)
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100 format(A," ",F13.10)
end program golden_ratio
```

opening a File for I/O



```
open (u, FILE=file_name[, option][, option][...])
```

- *u* is an integer, positive expression specifying a *file handle*

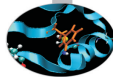
opening a File for I/O



```
open (u, FILE=file_name[, option][, option][...])
```

- ▶ *u* is an integer, positive expression specifying a *file handle*
- ▶ *file_name* is a string specifying file name (and possibly path) in your file system

opening a File for I/O



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```

- ▶ *u* is an integer, positive expression specifying a *file handle*
- ▶ *file_name* is a string specifying file name (and possibly path) in your file system
- ▶ *file handle* is then used as first argument to **read** and **write**

opening a File for I/O



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 - ▶ When you pass a ***** instead, you are using pre-opened units mapping to user terminal



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- ▶ *file handle* is then used as first argument to **read** and **write**
 - ▶ When you pass a ***** instead, you are using pre-opened units mapping to user terminal
 - ▶ Which usually means **5** for **read** and **6** for **write**, but *****, or **input_unit** and **output_unit** from **iso_fortran_env** Fortran 2003 module are more portable

opening a File for I/O



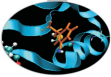
`open (u, FILE=file_name[, option][, option][...])`

- ▶ **u** is an integer, positive expression specifying a *file handle*
- ▶ **file_name** is a string specifying file name (and possibly path) in your file system
- ▶ *file handle* is then used as first argument to **read** and **write**
 - ▶ When you pass a ***** instead, you are using pre-opened units mapping to user terminal
 - ▶ Which usually means **5** for **read** and **6** for **write**, but *****, or **input_unit** and **output_unit** from **iso_fortran_env** Fortran 2003 module are more portable
 - ▶ For error messages, **0** is commonly used, but **error_unit** from **iso_fortran_env** module is portable

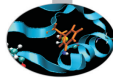
Some open Options



- ▶ **ACTION=act** specifies allowed actions
 - ▶ use '**read**' to only read
 - ▶ use '**write**' to only write
 - ▶ use '**readwrite**' (the default) to allow both



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 - ▶ use '**read**' to only read
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 - ▶ use '**readwrite**' (the default) to allow both
- ▶ **STATUS=st** tells how to behave wrt file existence:
 - ▶ use '**old**' to open a file that must already exist
 - ▶ use '**new**' to open a file that must not exist
 - ▶ use '**replace**' to open a new file, even if one already exists
 - ▶ use '**unknown**' (the default) to leave it up to the implementation (in all cases we know of, this means '**replace**')



- ▶ **ACTION=act** specifies allowed actions
 - ▶ use '**read**' to only read
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- ▶ **STATUS=st** tells how to behave wrt file existence:
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 - ▶ use '**replace**' to open a new file, even if one already exists
 - ▶ use '**unknown**' (the default) to leave it up to the implementation (in all cases we know of, this means '**replace**')
- ▶ **POSITION=pos** tells where to start I/O on an existing file
 - ▶ use '**rewind**' (the default) to start at beginning of file
 - ▶ use '**append**' to start at end of file

Iterative search for the Golden Ratio



```

program golden_ratio
! experiments with the golden ratio iterative relation
implicit none
integer, parameter :: rk = kind(1.0d0)
real(rk) :: phi, phi_old
real(rk) :: phi_start, tol
integer :: i, max_iter

open(11,FILE='golden.in',STATUS='old')
read(11,*) phi_start, tol, max_iter
close(11)

phi_old = phi_start
do i=1,max_iter
    phi = 1.0d0/phi_old + 1.0d0
    if (abs(phi - phi_old) < tol) exit
    phi_old = phi
end do

open(12,FILE='golden.out')
write(12,100) 'Start value:',phi_start
write(12,100) 'Tolerance:',tol
write(12,'(2(A," ",I11," "))') 'Ended at iteration:', i, 'of', max_iter
write(12,100) 'Final value:',phi
close(12)

100 format(A," ",F13.10)
end program golden_ratio

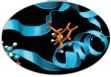
```

How to **close** a File



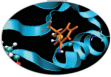
close (*u* [, **STATUS**=*st*])

- **close** completes all pending I/O operations and disassociates the file from the unit



close (*u* [, **STATUS=st**])

- ▶ **close** completes all pending I/O operations and disassociates the file from the unit
- ▶ **close** is automatically executed on all open files at program end, but closing a file explicitly when you are done with it is a good practice



`close (u[, STATUS=st])`

- ▶ `close` completes all pending I/O operations and disassociates the file from the unit
- ▶ `close` is automatically executed on all open files at program end, but closing a file explicitly when you are done with it is a good practice
- ▶ `st` tells what to do with the file after closing it
 - ▶ use '`keep`' to preserve the file (it's the default)
 - ▶ use '`delete`' to remove it (good for files used for temporary storage)



- ▶ Play with `golden.f90`:
 - ▶ trying good and bad inputs
 - ▶ giving less or more inputs than needed
 - ▶ changing format descriptors
 - ▶ try to understand the error message

- ▶ Homework: play with `itinv.f90`:
 - ▶ trying good and bad inputs
 - ▶ giving less or more inputs than needed
 - ▶ changing format descriptors
 - ▶ try to understand the error message



Array Syntax

Input/Output

Formatted I/O

File I/O

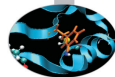
Namelist

Internal Files

Unformatted I/O

Robust I/O

Iterative search for the Golden Ratio



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! experiments with the golden ratio iterative relation
implicit none
integer, parameter :: rk = kind(1.0d0)
real(rk) :: phi, phi_old
real(rk) :: phi_start, tol
integer :: i, max_iter

namelist /golden_inputs/ phi_start, tol, max_iter

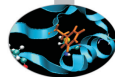
open(11,FILE='golden.in',STATUS='old')
read(11,golden_inputs)
close(11)

phi_old = phi_start
do i=1,max_iter
    phi = 1.0d0/phi_old + 1.0d0
    if (abs(phi - phi_old) < tol) exit
    phi_old = phi
end do

open(12,FILE='golden.out')
write(12,100) 'Start value:',phi_start
write(12,100) 'Tolerance:',tol
write(12,'(2(A," ",I11," "))') 'Ended at iteration:', i, 'of', max_iter
write(12,100) 'Final value:',phi
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100 format(A," ",F13.10)
end program golden_ratio
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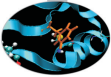
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100 format(A," ",F13.10)
end program golden_ratio
```



- **namelists** allow input/output of annotated lists of values



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- ▶ File content is structured, self-describing, order independent, comments are allowed:

```
&golden_inputs  
tol=1.e-4      ! tolerance  
phi_start=5.0  ! 0th iteration  
max_iter=10000000 /
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- ▶ Items missing in the input will retain previous value
- ▶ Items can be added to a namelist in different statements, but a code like this easily misleads readers (and you read your own codes, don't you?)
- ▶ Use them to make input robust, in output mostly good for debugging



Array Syntax

Input/Output

Formatted I/O

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Iterative search for the Golden Ratio



```

program golden_ratio
! experiments with the golden ratio iterative relation
implicit none
integer, parameter :: rk = kind(1.0d0)
real(rk) :: phi, phi_old
real(rk) :: phi_start, tol
integer :: i, max_iter, test_no
character(15) :: outfilename

namelist /golden_inputs/ phi_start, tol, max_iter, test_no

test_no = 1
open(11,FILE='golden.in',STATUS='old')
read(11,golden_inputs)
close(11)

phi_old = phi_start
do i=1,max_iter
    phi = 1.0d0/phi_old + 1.0d0
    if (abs(phi - phi_old) < tol) exit
    phi_old = phi
end do

write(outfilename,'("golden",I5.5,".out")') test_no
open(12,FILE=outfilename)
write(12,100) 'Start value:',phi_start
write(12,100) 'Tolerance:',tol
write(12,'(2(A," ",I11," "))') 'Ended at iteration:', i, 'of', max_iter
write(12,100) 'Final value:',phi
close(12)

100 format(A," ",F13.10)
end program golden_ratio

```

Iterative search for the Golden Ratio



```

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open(12,FILE=outfilename)
write(12,100) 'Start value:',phi_start
write(12,100) 'Tolerance:',tol
write(12,' (2(A," ",I11," "))') 'Ended at iteration:', i, 'of', max_iter
write(12,100) 'Final value:',phi
close(12)

100 format(A," ",F13.10)
end program golden_ratio
    
```



- ▶ **character** variables of default kind can be specified in place of units in **read** and **write** statements



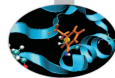
- ▶ **character** variables of default kind can be specified in place of units in **read** and **write** statements
- ▶ Writing to internal files is good to:
 - ▶ dynamically build file names according to a pattern (like number of iterations)
 - ▶ dynamically assemble complex I/O formats, depending on actual data
 - ▶ prepare complex labels for plot data formats
 - ▶ build commands to be sent to hardware devices
 - ▶ ...



- ▶ **character** variables of default kind can be specified in place of units in **read** and **write** statements
- ▶ Writing to internal files is good to:
 - ▶ dynamically build file names according to a pattern (like number of iterations)
 - ▶ dynamically assemble complex I/O formats, depending on actual data
 - ▶ prepare complex labels for plot data formats
 - ▶ build commands to be sent to hardware devices
 - ▶ ...
- ▶ Reading from internal files can be useful to read complex inputs
 - ▶ You have a textual input file sporting different formats
 - ▶ And the right format depends on actual data in the file
 - ▶ Just read each line in a **character** variable, suitably sized
 - ▶ Pick the suitable format
 - ▶ And use it to read from the variable itself



- ▶ Play with `goldenfile.f90`, `goldenfn1.f90`, and `goldenio.f90`:
 - ▶ writing input files
 - ▶ writing good and bad data in input files
 - ▶ giving input files wrong file names



Array Syntax

Input/Output

Formatted I/O

File I/O

Namelist

Internal Files

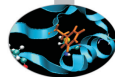
Unformatted I/O

Robust I/O



- ▶ Formatted I/O is good, but:
 - ▶ internal data format is much more compact
 - ▶ and roundoff may happen, making recovery of original values impossible
 - ▶ and conversion takes time

Iterative Matrix Inversion



```
program iterative_inversion
! experiments with matrix iterative inversion
implicit none
real, dimension(4,4) :: a, x, x_old, x_start
real :: tol, err
integer :: i, max_iter

open(21,FILE='input.dat',FORM='unformatted',STATUS='old')
read(21) a
read(21) x_start
read(21) tol,max_iter
close(21)

x_old = x_start
do i=1,max_iter
  x = 2.0*x_old - matmul(x_old,matmul(a,x_old))
  err = maxval(abs(x - x_old))
  if (err < tol) exit
  x_old = x
end do

open(22,FILE='itinv.dat',FORM='unformatted')
write(22) a
write(22) x_start
write(22) tol,max_iter
write(22) i
write(22) x
close(22)

end program iterative_inversion
```

Iterative Matrix Inversion



```

program iterative_inversion
! experiments with matrix iterative inversion
implicit none
real, dimension(4,4) :: a, x, x_old, x_start
real :: tol, err
integer :: i, max_iter

open(21,FILE='input.dat',FORM='unformatted',STATUS='old')
read(21) a
read(21) x_start
read(21) tol,max_iter
close(21)

x_old = x_start
do i=1,max_iter
  x = 2.0*x_old - matmul(x_old,matmul(a,x_old))
  err = maxval(abs(x - x_old))
  if (err < tol) exit
  x_old = x
end do

open(22,FILE='itinv.dat',FORM='unformatted')
write(22) a
write(22) x_start
write(22) tol,max_iter
write(22) i
write(22) x
close(22)

end program iterative_inversion

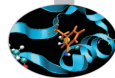
```



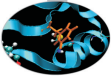
- ▶ Formatted I/O is good, but:
 - ▶ internal data format is much more compact
 - ▶ and roundoff may happen, making recovery of original values impossible
 - ▶ and conversion takes time
- ▶ Unformatted I/O is used to store and recover data in internal representation
 - ▶ Just give **FORM='unformatted'** option when opening the file
 - ▶ And omit format in **read** and **write** statements



- ▶ Formatted I/O is good, but:
 - ▶ internal data format is much more compact
 - ▶ and roundoff may happen, making recovery of original values impossible
 - ▶ and conversion takes time
- ▶ Unformatted I/O is used to store and recover data in internal representation
 - ▶ Just give **FORM='unformatted'** option when opening the file
 - ▶ And omit format in **read** and **write** statements
- ▶ Unformatted I/O is performed on a *record* basis
 - ▶ In unformatted mode, each **write** writes a *record*
 - ▶ As we'll see, this allows walking your files backward and forward
 - ▶ But has interesting consequences, as more than your data is written to your file...



- ▶ Modify `itinv.f90` to perform unformatted I/O
- ▶ To test it, you'll need an additional program:
 - ▶ taking text input from keyboard or initializing all needed data
 - ▶ to write a good unformatted input file for the new version of `itinv.f90`



- ▶ Try different ways to output the results:

- ▶ element-wise

```
do j=1,n
  do i=1,n
    write(79) a(i,j)
  end do
end do
```

- ▶ column-wise, using an implied do-loop:

```
do j=1,n
  write(79) (a(i,j), i=1,n)    ! a(:,j) will also do
end do
```

- ▶ with two implied do-loops:

```
write(79) ((a(i,j), i=1,n), j=1,n)
```

- ▶ Can you spot the difference?



► Try different ways to output the results:

► element-wise

```
do j=1,n
  do i=1,n
    write(79) a(i,j)
  end do
end do
```

► column-wise, using an implied do-loop:

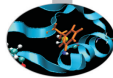
```
do j=1,n
  write(79) (a(i,j), i=1,n)    ! a(:,j) will also do
end do
```

► with two implied do-loops:

```
write(79) ((a(i,j), i=1,n), j=1,n)
```

► Can you spot the difference?

► Not a big issue for 4×4 matrices, but think of a $256 \times 256 \times 1024$ grid!

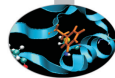


- ▶ **read** always advance to next record, even if you read only part of the record (or possibly nothing)
- ▶ **backspace(u)** moves position for subsequent I/Os to the record preceding the current one
- ▶ **rewind(u)** moves position for subsequent I/Os to file beginning
- ▶ To allow positioning back and forth, a four bytes record marker is added in 32 bit mode (eight bytes in 64 bit mode) before and after each record
- ▶ Best practice: write data in whole blocks



- ▶ Record markers added in unformatted I/O make exchanging data with other programs (notably C ones) troublesome
- ▶ `open(unit, ..., ACCESS='stream', ...)` is a new method to access external files
- ▶ No record markers are written before or after a **write**
 - ▶ Thus, advancing or backspacing over records is not possible
 - ▶ But required position may be specified by:


```
write(unit,POS=position) x
read(unit,POS=position) y
```
- ▶ Best practice: if you are really serious about data exchanges, across different programs and systems, use libraries like HDF5, VTK, CGNS



Array Syntax

Input/Output

- Formatted I/O

- File I/O

- Namelist

- Internal Files

- Unformatted I/O

- Robust I/O**



- ▶ You may happen to:
 - ▶ Try to open a new file, when one with same name already exists
 - ▶ Look for an existing file, which is missing
 - ▶ Encounter an unexpected end of record in a **read**
 - ▶ Encounter an unexpected end of file while reading
 - ▶ Run out of disk space while writing
 - ▶ Try writing to a read-only file
 - ▶ ...

I/O Errors and Mishaps



- ▶ You may happen to:
 - ▶ Try to open a new file, when one with same name already exists
 - ▶ Look for an existing file, which is missing
 - ▶ Encounter an unexpected end of record in a **read**
 - ▶ Encounter an unexpected end of file while reading
 - ▶ Run out of disk space while writing
 - ▶ Try writing to a read-only file
 - ▶ ...
- ▶ And get an unfriendly runtime error



- ▶ You may happen to:
 - ▶ Try to open a new file, when one with same name already exists
 - ▶ Look for an existing file, which is missing
 - ▶ Encounter an unexpected end of record in a **read**
 - ▶ Encounter an unexpected end of file while reading
 - ▶ Run out of disk space while writing
 - ▶ Try writing to a read-only file
 - ▶ ...
- ▶ And get an unfriendly runtime error
- ▶ Or you may need to open a file in a library you are writing
 - ▶ And use a unit already opened in a calling program
 - ▶ The previously opened unit is automatically closed
 - ▶ With surprising consequences on program behavior



- ▶ All I/O statements accept an **IOSTAT=ios** option
 - ▶ **ios** must be an integer variable of default kind
 - ▶ Set to zero on success
 - ▶ Set to negative values on end of file or record
(in Fortran 2003, **iostat_end** and **iostat_eor** respectively,
from **iso_fortran_env** module)
 - ▶ Set to positive values on error
 - ▶ Execution will not stop
- ▶ Use it to identify the issue, and recover or fail gracefully



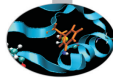
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 - ▶ Set to positive values on error
 - ▶ Execution will not stop
- ▶ Use it to identify the issue, and recover or fail gracefully
- ▶ All I/O statements accept an **ERR=err-label** option
 - ▶ **err-label** is a statement label in the same program unit
 - ▶ Flow control jumps to **err-label** in case of error
- ▶ Use it to centralize error management and recovery
- ▶ Together with **iostat**, of course

In Doubt? *inquire!*



- Let's assume **ans** is a logical variable, **k** is an integer variable, and **s** is a character variable of suitable length

In Doubt? ***inquire!***



- ▶ Let's assume **ans** is a logical variable, **k** is an integer variable, and **s** is a character variable of suitable length
- ▶ **inquire(FILE='input.dat',EXIST=ans)** will set **ans** to **.true.** if file **input.dat** exists

In Doubt? ***inquire!***



- ▶ Let's assume **ans** is a logical variable, **k** is an integer variable, and **s** is a character variable of suitable length
- ▶ **inquire(FILE='input.dat',EXIST=ans)** will set **ans** to **.true.** if file **input.dat** exists
- ▶ **inquire(FILE='input.dat',OPENED=ans)** will set **ans** to **.true.** if file **input.dat** is already opened

In Doubt? ***inquire!***



- ▶ Let's assume **ans** is a logical variable, **k** is an integer variable, and **s** is a character variable of suitable length
- ▶ **inquire(FILE='input.dat',EXIST=ans)** will set **ans** to **.true.** if file **input.dat** exists
- ▶ **inquire(FILE='input.dat',OPENED=ans)** will set **ans** to **.true.** if file **input.dat** is already opened
- ▶ **inquire(15,OPENED=ans)** will set **ans** to **.true.** if a file is already opened on unit **15**

In Doubt? ***inquire!***



- ▶ Let's assume **ans** is a logical variable, **k** is an integer variable, and **s** is a character variable of suitable length
- ▶ **inquire(FILE='input.dat',EXIST=ans)** will set **ans** to **.true.** if file **input.dat** exists
- ▶ **inquire(FILE='input.dat',OPENED=ans)** will set **ans** to **.true.** if file **input.dat** is already opened
- ▶ **inquire(15,OPENED=ans)** will set **ans** to **.true.** if a file is already opened on unit 15
- ▶ **inquire(FILE='input.dat',NUMBER=k)** will set **k** to **-1** if file **input.dat** is not opened, to connected unit otherwise

More Doubts? *inquire* More!



- ***inquire*** (15, **FORM=s**) will set **s** to ' **FORMATTED** ' or ' **UNFORMATTED** ' if unit 15 is connected for formatted or unformatted I/O respectively, to ' **UNDEFINED** ' otherwise

More Doubts? *inquire* More!



- ▶ ***inquire***(15, **FORM=s**) will set **s** to ' **FORMATTED** ' or ' **UNFORMATTED** ' if unit 15 is connected for formatted or unformatted I/O respectively, to ' **UNDEFINED** ' otherwise
- ▶ ***inquire***(15, **ACTION=s**) will set **s** to ' **READ** ' or ' **WRITE** ' or ' **READWRITE** ', depending on what actions are allowed on unit 15, to ' **UNDEFINED** ' if unconnected

More Doubts? *inquire* More!



- ▶ ***inquire***(15, **FORM=s**) will set **s** to 'FORMATTED' or 'UNFORMATTED' if unit 15 is connected for formatted or unformatted I/O respectively, to 'UNDEFINED' otherwise
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- ▶ ***inquire***(**IOLENGTH=k**) *output-list* will set **k** to the number of processor dependent units (bytes, in practice) occupied by an unformatted write of *output-list*

More Doubts? *inquire* More!



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- ▶ And many more variations, look to manuals

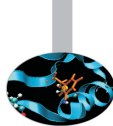
More Doubts? *inquire* More!



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- ▶ ***inquire***(**IOLENGTH=k**) *output-list* will set **k** to the number of processor dependent units (bytes, in practice) occupied by an unformatted write of *output-list*
- ▶ And many more variations, look to manuals
- ▶ Of course, **IOSTAT** and **ERR** can be useful on ***inquire*** too



- ▶ Write a program that:
 - ▶ reads an 'arbitrarily' long column of real numbers from an ASCII file
 - ▶ prints maximum, minimum, average of the numbers
 - ▶ and prints the $\lfloor n/2 \rfloor$ -th row where n is the length of the column



Part IV

Memory Management and Derived Types

Derived types, operators overloading, parametric types and inheritance. Memory management, dynamic allocation and memory heap. Pointers. C and Fortran interoperability.



Managing Memory

Dynamic Memory Allocation

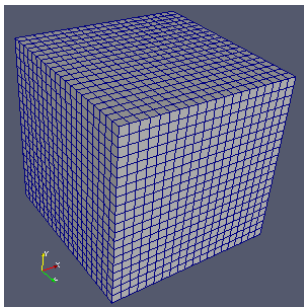
Fortran Pointers

Extending the Language

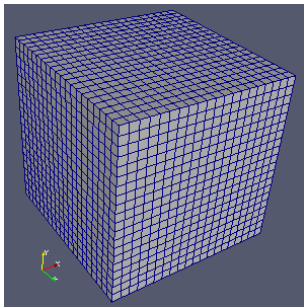
Bridging the Gap with C

Conclusions

A PDE Problem



- Let's imagine we have to solve a PDE



- ▶ Let's imagine we have to solve a PDE
- ▶ On a dense, Cartesian, uniform grid
 - ▶ Mesh axes are parallel to coordinate ones
 - ▶ Steps along each direction have the same size
 - ▶ And we have some discretization schemes in time and space to solve for variables at each point

A Rigid Solution



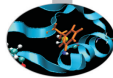
```
integer, parameter :: NX = 200
integer, parameter :: NY = 450
integer, parameter :: NZ = 320

integer, parameter :: rk = selected_real_kind(12)

real(rk) :: deltax ! Grid steps
real(rk) :: deltay
real(rk) :: deltaz

real(rk) :: u(NX,NY,NZ)
real(rk) :: v(NX,NY,NZ)
real(rk) :: w(NX,NY,NZ)
real(rk) :: p(NX,NY,NZ)
```

- We could write something like that in a module, and use it everywhere



```
integer, parameter :: NX = 200
integer, parameter :: NY = 450
integer, parameter :: NZ = 320

integer, parameter :: rk = selected_real_kind(12)

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real(rk) :: v(NX,NY,NZ)
real(rk) :: w(NX,NY,NZ)
real(rk) :: p(NX,NY,NZ)
```

- ▶ We could write something like that in a module, and use it everywhere
- ▶ But it has annoying consequences
 - ▶ Recompile each time grid resolution changes
 - ▶ A slow process, for big programs
 - ▶ And error prone, as we may forget about



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```

- ▶ We could write something like that in a module, and use it everywhere
- ▶ But it has annoying consequences
 - ▶ Recompile each time grid resolution changes
 - ▶ A slow process, for big programs
 - ▶ And error prone, as we may forget about
- ▶ Couldn't we size data structures according to user input?



```

subroutine my_pde_solver(nx, ny, nz)
  integer, intent(in) :: nx, ny, nz

  integer, parameter :: rk = selected_real_kind(12)
  real(rk):: deltax, deltay, deltaz ! Grid steps

  real(rk) :: u(nx,ny,nz)
  real(rk) :: v(nx,ny,nz)
  real(rk) :: w(nx,ny,nz)
  real(rk) :: p(nx,ny,nz)
  
```

- We could think of declaring automatic arrays inside a subroutine



```
subroutine my_pde_solver(nx, ny, nz)
  integer, intent(in) :: nx, ny, nz

  integer, parameter :: rk = selected_real_kind(12)
  real(rk):: deltax, deltax, deltaz ! Grid steps

  real(rk) :: u(nx,ny,nz)
  real(rk) :: v(nx,ny,nz)
  real(rk) :: w(nx,ny,nz)
  real(rk) :: p(nx,ny,nz)
```

- ▶ We could think of declaring automatic arrays inside a subroutine
- ▶ This is unwise
 - ▶ Automatic arrays are usually allocated on the process stack
 - ▶ Which is a precious resource
 - ▶ And limited in most system configurations

A Bad, Old, Common approach



```
program pde_solve
  parameter (MAXNX=400, MAXNY=400, MAXNZ=400)
  parameter (MAXSIZE=MAXNX*MAXNX*MAXNZ)

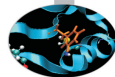
  real*8 u(MAXSIZE), v(MAXSIZE), w(MAXSIZE), p(MAXSIZE)

  common u,v,w,p
! ...
  call my_pde_solver(nx,ny,nz,u,v,w,p)
! ...
end

subroutine my_pde_solver(nx,ny,nz,u,v,w,p)
  real*8 u(nx,ny,nz), v(nx,ny,nz), w(nx,ny,nz), p(nx,ny,nz)
! ...
```

- We could give a different shape to dummy arguments

A Bad, Old, Common approach



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program pde_solve
  parameter (MAXNX=400, MAXNY=400, MAXNZ=400)
  parameter (MAXSIZE=MAXNX*MAXNX*MAXNZ)

  real*8 u(MAXSIZE), v(MAXSIZE), w(MAXSIZE), p(MAXSIZE)

  common u,v,w,p
! ...
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! ...
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- ▶ But this only works if interface is implicit
 - ▶ Which is dangerous

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  common u,v,w,p
! ...
  call my_pde_solver(nx,ny,nz,u,v,w,p)
! ...
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subroutine my_pde_solver(nx,ny,nz,u,v,w,p)
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!...
```

- ▶ We could give a different shape to dummy arguments
- ▶ But this only works if interface is implicit
 - ▶ Which is dangerous
- ▶ Maximum problem size still program limited: **$nx*ny*nz$** must be less than **MAXSIZE**



- ▶ Being program limited is annoying
- ▶ It's much better to accommodate to any user specified problem size
 - ▶ Right, as long as there is enough memory
 - ▶ But if memory is not enough, not our fault
 - ▶ It's computer or user's fault
- ▶ And there are many complex kinds of computations
 - ▶ Those in which memory need cannot be foreseen in advance
 - ▶ Those in which arrays do not fit
 - ▶ Those in which very complex data structures are needed



Managing Memory

Dynamic Memory Allocation

Fortran Pointers

Extending the Language

Bridging the Gap with C

Conclusions

Enter Allocatable Arrays



```
integer, parameter :: rk = selected_real_kind(12)

real(rk), dimension(:,:,:), allocatable :: u,v,w,p

allocate(u(nx,ny,nz),v(nx,ny,nz),w(nx,ny,nz),p(nx,ny,nz))
```

- When allocatable arrays are declared, only their rank is specified (**dimension(:,:,:)**)

Enter Allocatable Arrays



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integer, parameter :: rk = selected_real_kind(12)

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- ▶ When allocatable arrays are declared, only their rank is specified (**dimension(:,:,:)**)
- ▶ **allocate** statement performs actual memory allocation and defines extents

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- ▶ When allocatable arrays are declared, only their rank is specified (**dimension(:,:,:)**)
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 - ▶ On failure, program **stops**

Enter Allocatable Arrays



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```

- ▶ When allocatable arrays are declared, only their rank is specified (**dimension(:,:,:)**)
- ▶ **allocate** statement performs actual memory allocation and defines extents
 - ▶ On failure, program **stops**
 - ▶ But if **STAT=integer_var** is specified, **integer_var** is set to zero on success and to a positive value on failure, and execution doesn't stop

Enter Allocatable Arrays



```
integer, parameter :: rk = selected_real_kind(12)

real(rk), dimension(:,:,:), allocatable :: u,v,w,p

allocate (u(nx,ny,nz), v(nx,ny,nz), w(nx,ny,nz), p(nx,ny,nz))
```

- ▶ When allocatable arrays are declared, only their rank is specified (**dimension(:,:,:)**)
- ▶ **allocate** statement performs actual memory allocation and defines extents
 - ▶ On failure, program **stops**
 - ▶ But if **STAT=integer_var** is specified, **integer_var** is set to zero on success and to a positive value on failure, and execution doesn't stop
- ▶ Best practice: use **STAT=** and, on failure, provide information to users before terminating execution

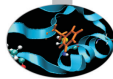
Freeing Memory



- ▶ Where all these 'dynamic allocated memory' comes from?
 - ▶ From an internal area, often termed "*memory heap*"
 - ▶ When that is exhausted, OS is asked to give the process more memory
 - ▶ And if OS is short of memory, or some configuration limit is exhausted...



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 - ▶ Allocatable which are local to a procedure are automatically deallocated on return
 - ▶ But it's implementation defined what happens to allocatable private to a module



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 - ▶ But it's implementation defined what happens to allocatable private to a module
- ▶ Best practice: always deallocate when you are done with an allocatable array

Three Common Mistakes



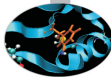
- Trying to allocate or deallocate an array that was not allocatable

Three Common Mistakes



- ▶ Trying to allocate or deallocate an array that was not allocatable
 - ▶ Compiler will catch it

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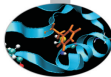
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- ▶ Mistaking allocatables for a substitute to procedure automatic arrays
 - ▶ Dynamic allocation incurs costs
 - ▶ Only worth for big arrays that would not fit program stack



- ▶ When assigning an array value to a not allocated allocatable array, the allocatable array gets automatically allocated
- ▶ This simplifies the use of array functions which return a variable-sized result

```

real, dimension(100) :: x
real, allocatable, dimension(:) :: all_values, nonzero_values

! size is 100, small benefit wrt explicit allocation
all_values      = x

! size depends on x values, AA is a great benefit now
nonzero_values = pack(x,x/=0)
  
```



- ▶ Automatic re-allocation is performed when the shape of the assignment does not fit, e.g.
 - `a = (/ a , 5 , 6 /)`
- ▶ Beware: it may dramatically affect performances!
 - ▶ if you don't need it, disable it using compiler options
- ▶ AA naturally extends to **characters** strongly increasing their adaptability
 - ▶ when declaring **characters**, the **len** value declaration may be postponed (**deferred type parameter**)
 - ▶ during assignment the Right Hand Side passes its **len** on the deferred-length string (under the hood, automatic re-allocation may occur)
 - ▶ explicit allocation is possible but often worthless, required when reading from input, though

```

character(len=:), allocatable :: str
character(len=50) :: fixed_str
allocate(character(80) :: str) ! allocates str using len=80
str = fixed_str ! re-allocates str using len=50
  
```



Managing Memory

Dynamic Memory Allocation

Fortran Pointers

Extending the Language

Bridging the Gap with C

Conclusions

Enter Fortran Pointers



- ▶ Fortran pointers are aliases to other objects
- ▶ Declared like regular variables, with attribute **pointer**
- ▶ Associated to actual objects with pointer assignment =>
- ▶ To be associated with a pointer, variables must have the **target** attribute
 - ▶ But compilers are often liberal (sloppy?) on this
- ▶ Disassociated by actual objects with **nullify** statement or by pointer assignment of **null()**

```
real, dimension(:,:,:), pointer :: r
```

```
real, target :: a(5,15,6), b(3,22,7)
```

```

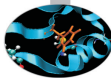
r => a           ! pointer assignment
                  ! now r is an alias of a
r(1,1,1) = 2.    ! usual assignment
                  ! now both r(1,1,1) and a(1,1,1) values are 2.
nullify(r)       ! a is still alive

```

```

r => b           ! now r is an alias of b
r => null()

```

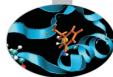


- Pointers may also alias sections of arrays (and subobjects, see later)

```
real, dimension(:,:,:), pointer :: r  
real, target :: a(5,15,6)
```

```
r => a(2:4,1:10,3:6) ! r(1,1,1) aliases a(2,1,3)  
                   ! r(3,10,4) aliases a(4,10,6)
```


More Fortran Pointers

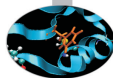


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real, dimension(:,:,:), pointer :: r  
real, target :: a(5,15,6)
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```
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- The reverse is not true: it is not possible to explicitly associate sections of pointers



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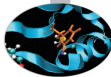
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real, target :: a(5,15,6)

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```

- The reverse is not true: it is not possible to explicitly associate sections of pointers
- But lower bounds may be specified (from F2003)

```

s(2:, :, :) => a(2:4,1:10,3:6) ! s(2,1,1) aliases a(2,1,3)
  
```



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real, dimension(:, :, :), pointer :: r
real, target :: a(5,15,6)

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- The reverse is not true: it is not possible to explicitly associate sections of pointers
- But lower bounds may be specified (from F2003)
- A target of a multidimensional array pointer may be one-dimensional

```

a(1:n,1:n) => a_linear(1:n*n)
  
```



- A pointer may be scalar, too

```
real, target  :: s  
real, pointer :: p  
...  
p => s
```



- A pointer may be scalar, too

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- ▶ the following code will leave **a** still pointing to **c**

```

    b => c           ! c has the target attribute
    a => b
    nullify(b)
  
```

Allocating Pointers



- If you allocate a pointer, an unnamed object of the pointee type is created, and associated with the pointer itself

```
real, dimension(:,:,:), pointer :: r
```

```
allocate(r(5,15,6))
```

```
! now r refers an unnamed array allocated on the heap
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- ▶ The unnamed objects created when allocating a pointer are possible targets for other pointers
- ▶ You can use pointers in place of allocatables, but, unless necessary, prefer **allocatable**: the compiler usually optimizes better
- ▶ You can deallocate the pointee by specifying the pointer in a **deallocate** statement

BIG Mistakes with Pointers



- ▶ Referencing an undefined pointer (strange things may happen, it may also seem to work)
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- ▶


```

real, dimension(:, :), pointer :: r, p
!...
allocate(r(n,m))
p => r
! ...
deallocate(r)
p(k,1) = p(k,1)+1
      
```

Now you'll be in troubles with `p`, with really strange behavior



- Discretization on Cartesian 2D grid with Dirichlet Boundary Conditions

$$\begin{cases} f(x_{i+1,j}) + f(x_{i-1,j}) - 2f(x_{i,j}) + \\ f(x_{i,j+1}) + f(x_{i,j-1}) - 2f(x_{i,j}) = 0 & \forall x_{i,j} \in (a,b)^2 \\ f(x_{i,j}) = \alpha(x_{i,j}) & \forall x_{i,j} \in \partial[a,b]^2 \end{cases}$$

- Iterative advancement using Jacobi method

$$\begin{cases} f_{n+1}(x_{i,j}) = \frac{1}{4} [& f_n(x_{i+1,j}) + f_n(x_{i-1,j}) + \\ & f_n(x_{i,j+1}) + f_n(x_{i,j-1})] & \forall n > 0 \\ f_0(x_{i,j}) = 0 & \forall x_{i,j} \in (a,b)^2 \\ f_n(x_{i,j}) = \alpha(x_{i,j}) & \forall x_{i,j} \in \partial[a,b]^2, & \forall n > 0 \end{cases}$$

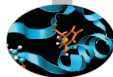
Laplace: static implementation



```

program laplace
  implicit none
  integer, parameter :: dp=kind(1.d0), n = 100
  integer              :: maxIter = 100000, i, j, iter = 0
  real(dp), dimension(0:n+1,0:n+1) :: T, Tnew
  real(dp)              :: tol = 1.d-4, var = 1.d0, top = 100.d0
  T(0:n,0:n) = 0.d0
  T(n+1,1:n) = (/ (i, i=1,n) /) * (top / (n+1))
  T(1:n,n+1) = (/ (i, i=1,n) /) * (top / (n+1))
  do while (var > tol .and. iter <= maxIter)
    iter = iter + 1;    var = 0.d0
    do j = 1, n
      do i = 1, n
        Tnew(i,j) = 0.25d0*( T(i-1,j) + T(i+1,j) + &
                               T(i,j-1) + T(i,j+1) )
        var = max(var, abs( Tnew(i,j) - T(i,j) ))
      end do
    end do
    if (mod(iter,100)==0) &
      write(*,"(a,i8,e12.4)") ' iter, variation:', iter, var
    T(1:n,1:n) = Tnew(1:n,1:n)
  end do
end program laplace
  
```

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  end do
end program laplace

```



- ▶ Modify the code using advanced Fortran features:
 - ▶ array syntax
 - ▶ allocatable arrays
 - ▶ pointer arrays
- ▶ Try to list pros and cons of each approach



Managing Memory

Extending the Language

- Derived Types

- Operators Overloading

- Parameterized Types

- Extending Types, and Objects

- Sketchy Ideas on Data Structures

Bridging the Gap with C

Conclusions



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- ▶ Fortran allows programmers to add new types, built as assemblies of existing ones

```
type position
  real :: x, y, z
end type position
```

```
type velocity
  real :: x, y, z
end type velocity
```

- ▶ Components in different derived types may have the same name (not a surprise!)
- ▶ **type(position) :: r** declares a variable of type **position**
- ▶ Components of a derived type can be accessed like this:
r%y = 0.0



- ▶ Derived types are not second class citizens
- ▶ Thus derived types (also termed *structures*) can be assembled from other derived types too

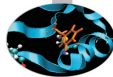
```

type particle
  type(position) :: r
  type(velocity) :: v
  real :: mass
end type particle
  
```

```

type atom
  type(position) :: r
  type(velocity) :: v
  real :: mass ! In atomic units
  integer :: an ! Atomic number
end type atom
  
```

- ▶ **type(particle) :: p** declares a variable of type **particle**
- ▶ Components of a component of a variable can be accessed like this: **p%v%z = 0.0**



```
type(atom) :: h1, h2, he

h1%r = position(0.0, 0.0, 0.0)
h1%v = velocity(1.0, -1.0, 0.0)
h1%mass = 1.00794
h1%an = 1 ! Assigns atomic number

h2 = h1 ! Intrinsic assignment

he = atom(position(1.0, 0.0, -1.0), h2%v, 4.002602, 2)
```

- ▶ Derived type name can be used to construct values of the type
- ▶ Unsurprisingly, **velocity()** is termed a *constructor*
- ▶ Values passed as argument to constructors must be ordered as in type definition
- ▶ Assignment is intrinsically available



- ▶ A type component may be allocatable (or pointer)
 - ▶ automatic allocation can be useful in this context
 - ▶ avoids separate coding for each allocatable component

```

type polygon
  real, allocatable :: xc(:)
  real, allocatable :: yc(:)
endtype polygon
type(polygon) :: a,b
allocate(a%xc(3), a%yc(3))
a%xc(1) = 0. ; a%xc(2) = 1. ; a%xc(3) = 1.
a%yc(1) = 0. ; a%yc(2) = 0. ; a%yc(3) = 1.
b = a
  
```

- ▶ A pointer can alias an object component

```

type(velocity), pointer :: v
type(atom), target :: oneatom
v => oneatom%velocity
  
```

Types in rescue of pointers



- Sometimes you need an array of pointers. But:

```
real, dimension(:), pointer :: p
```

does not declare an array of pointers, but a pointer capable of aliasing an array

Types in rescue of pointers



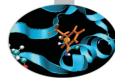
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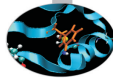
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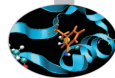
- What about array of pointers?
 - as such are not allowed in Fortran, but the equivalent effect can be achieved by creating a type containing a pointer component and building an array of this type
- For example, a lower-triangular matrix may be held using a pointer for each row

```

type row
  real, dimension(:), pointer :: r
end type row
type(row), dimension(n) :: t
do i=1,n
  allocate(t(i)%r(1:i)) ! Allocate row i of length i
enddo
  
```



- We know that structure components can be pointers

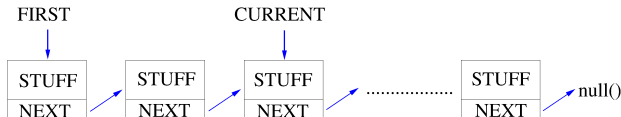


- ▶ We know that structure components can be pointers
- ▶ And a pointer in a structure can point to a structure of the same type:

```

type atom_list
  type(atom) :: a
  type(atom_list), pointer :: next
end type
  
```

which comes in handy to define complex data structures, like lists





- Declare two pointers to list elements (typically head and current elements)
- Allocate the head and let the current pointer alias the head, too
- Fill the inner content of the list element
- To add an element to the end allocate the **next** component
- Let the current pointer be associated to this new element

```

type(atom_list), pointer :: first, current
allocate(first)    ; first%next => null()
current => first   ; current%a = 2
allocate(current%next)
current => current%next ; current%next => null() ; current%a = 3
  
```

- And if you want to access to an existing list, use **associated**

```

current => first
do while (associated(current))
  print*, 'List Element: ', current%a
  current => current%next
end do
  
```

Formatted I/O of Derived Types



- ▶ Derived types boil down (possibly recursively) to collections of intrinsic types
- ▶ And behavior is coherent with I/O of complex values and arrays
- ▶ All single intrinsic type (sub)components will be processed in sequence
- ▶ If you want control of the conversion:
 - ▶ a proper edit descriptor must be provided for each component
 - ▶ in same order as components are declared in type declaration
- ▶ Fortran 2003 introduces the **DT** edit descriptor to give users total control



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Same Name, Different Personality



- Binary operator + can be used to add:

Same Name, Different Personality



- ▶ Binary operator + can be used to add:
 - ▶ a pair of integer values



- ▶ Binary operator + can be used to add:
 - ▶ a pair of integer values
 - ▶ a pair of real values

Same Name, Different Personality



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 - ▶ a pair of complex values

Same Name, Different Personality



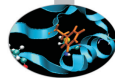
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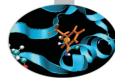
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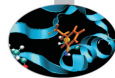
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- ▶ It's like the meaning of $+$ is 'overloaded'
 - ▶ Different machine code is generated depending on operand types
- ▶ And ditto for $-$, $*$, $/$, $>$, $>=$, ...

Bringing Abstractions Further



Wouldn't it be nice to have arithmetic operators work on structures?

```
interface operator(-)
  function subvel(p1, p2)
    type(velocity), intent(in) :: p1, p2
    type(velocity) :: subvel
  end function
end interface operator(-)
```

```
interface operator(-)
  function chsvel(p)
    type(velocity), intent(in) :: p
    type(velocity) :: chsvel
  end function
end interface operator(-)
```

```
function subvel(p1, p2)
  implicit none
  type(velocity), intent(in) :: p1, p2
  type(velocity) :: subvel
  subvel%x = p1%x-p2%x; subvel%y = p1%y-p2%y; subvel%z = p1%z-p2%z
end function subvel
```

```
function chsvel(p)
  implicit none
  type(velocity), intent(in) :: p
  type(velocity) :: chsvel
  chsvel%x = -p%x; chsvel%y = -p%y; chsvel%z = -p%z
end function chsvel
```

Changing Rules as We Need



- ▶ We are fitting an infinite space into a finite box with periodic boundary conditions
- ▶ Wouldn't it be nice to define our operators with custom functionality?

```
interface operator(+)
  function addpos(p1, p2)
    type(position), intent(in) :: p1, p2
    type(position) :: addpos
  end function
end interface operator(+)

function addpos(p1, p2) ! Adds positions with periodic boundary conditions
  implicit none
  type(position), intent(in) :: p1, p2
  type(position) :: addpos
  real,parameter :: boxwidth = 128.0

  addpos%x = modulo(p1%x+p2%x, boxwidth)
  addpos%y = modulo(p1%y+p2%y, boxwidth)
  addpos%z = modulo(p1%z+p2%z, boxwidth)
end function addpos
```

Operator Overloading



- ▶ **interface operator(*op-name*)** lets you overload *op-name* with a generic procedure
 - ▶ Arguments must be **intent (in)** and can be either one or two
 - ▶ *op-name* may be an intrinsic operator, or a **.new_name.**

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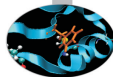
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- ▶ And defining subtraction is an easy job
- ▶ Positions may be added as usual intrinsic variables and boundary conditions are automatically imposed

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- ▶ Now velocities may be added as intrinsic arithmetic types
- ▶ And defining subtraction is an easy job
- ▶ Positions may be added as usual intrinsic variables and boundary conditions are automatically imposed
- ▶ Time for a module

A Module Centered on Derived Types



```

module periodic_box
  implicit none
  real, private, parameter :: boxwidth = 128.0
  private addpos, addvel, chsvel, subvel, subpos

  type position
    real :: x, y, z
  end type position

  type velocity
    real :: x, y, z
  end type velocity

  interface operator(+)
    module procedure addpos
    module procedure addvel
  end interface operator(+)
! ...
contains
  function addpos(p1, p2) ! Adds positions with periodic boundary conditions on x
    type(position), intent(in) :: p1, p2
    type(position) :: addpos
    addpos%x = modulo(p1%x+p2%x, boxwidth)
    addpos%y = modulo(p1%y+p2%y, boxwidth)
    addpos%z = modulo(p1%z+p2%z, boxwidth)
  end function addpos

  function addvel
    !...
  end function addvel
! ...
end module periodic_box

```



- ▶ Again, modules are the best way of grouping related stuff
- ▶ Again, with modules and module procedures we don't need to write interface blocks
- ▶ Modules let us hide implementation details
- ▶ Best practice: put structure definitions and related functions and operators in modules
 - ▶ Anyway, they will be used together
 - ▶ When dealing with nested types with many related functions, a hierarchy of modules would probably help
 - ▶ Because, of course, you can **use** modules in a module

Hands-on Session #2



- ▶ Write a module that defines:
 - ▶ A new type *vector* made up of three real components
 - ▶ Operator `.cross.` for cross product
 - ▶ Operator `+` to sum two *vectors*
- ▶ Write a program to test your module

```
program test_class_vector
  use class_vector

  implicit none

  type(vector) :: v, w, z

  v=vector(1.d0,0.d0,0.d0)
  w=vector(0.d0,1.d0,0.d0)
  z=vector(0.d0,0.d0,1.d0)

  write(*,*) v+w.cross.z

end program test_class_vector
```

- ▶ Definition of cross product:

$$a \times b = (a_2 b_3 - a_3 b_2) \hat{i} + (a_3 b_1 - a_1 b_3) \hat{j} + (a_1 b_2 - a_2 b_1) \hat{k}$$

- ▶ Then extend operators to have them work with array of vectors: it's elementary!



Managing Memory

Extending the Language

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Sketchy Ideas on Data Structures

Bridging the Gap with C

Conclusions



- What if we wanted different **kinds of points**?

- This is a possibility:

```
type point
  real( selected_real_kind(5) ) :: x, y, z
end type point
```

```
type widepoint
  real( selected_real_kind(12) ) :: x, y, z
end type widepoint
```

- But not very elegant, nor easy to manage



- In Fortran 2003, types may have kind type parameters:

```

type point(point_kind)
  integer, kind :: point_kind = kind(0.0)
  real(point_kind) :: x, y, z
end type point
  
```

```

type(point(point_kind=kind(0.0))) :: apoint
type(point) :: anotherpoint
type(point(selected_real_kind(12))) :: awiderpoint
  
```

- **kind** states that this type parameter behaves as a kind
- And it works as **kind** does for intrinsic types



- Structures may have array components

```

type segments(point_kind)
  integer, kind :: point_kind = kind(0.0)
  type(point(point_kind)), dimension(100) :: start_point
  type(point(point_kind)), dimension(100) :: end_point
end type segments
  
```

- Our `segments` type looks a bit rigid, doesn't it?

- Derived type parameters come to rescue:

```

type segments(point_kind, n)
  integer, kind :: point_kind = kind(0.0)
  integer, len :: n
  type(point(point_kind)), dimension(n) :: start_point
  type(point(point_kind)), dimension(n) :: end_point
end type segments
  
```

```

type(segments(n=100)) :: ahundredsegments
type(segments(n=1000)) :: athousandsegments
  
```



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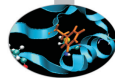
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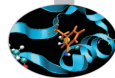
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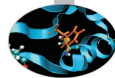
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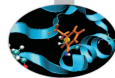
- So, we are able to define new types, and specialized procedures and operators to use them



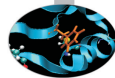
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- ▶ And **particle**, and **atom** share identical components
 - ▶ And a **ion** would simply add a **charge** component
- ▶ Wouldn't it be nice to 'inherit' from one type to another?
 - ▶ Yeah, and easier to manage, too!
 - ▶ And this is what CS priests call *Object-Oriented* programming, and is so trendy!

Fortran 2003 **extends** Derived Types



```
type point
  real :: x, y, z
end type point
```

```
type, extends(point) :: position
end type position
```

```
type, extends(point) :: velocity
end type velocity
```

```
type particle
  type(position) :: r
  type(velocity) :: v
  real :: mass
end type particle
```

```
type, extends(particle) :: atom
  integer :: an ! atomic number
end type atom
```

```
type, extends(atom) :: ion
  integer :: charge ! in units of elementary charge
end type ion
```

- ▶ **extends** means that the new type has the same components, and possibly more
- ▶ Now we still have to write procedures and operators, don't we?



- ▶ A type extension includes an implicit component with the same name and type as its parent type
 - ▶ this can come in handy when the programmer wants to operate on components specific to a parent type

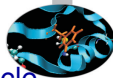
```

type(ion) :: p                                ! declare p as a ion object

p%mass                                         ! access mass component for p
p%atom%mass                                   ! another way
p%atom%particle%mass                          ! ...
  
```

- ▶ We often say the child and parent types have a “is a” relationship
 - ▶ an atom “is” a particle
 - ▶ but a particle is not an atom because the atomic component may be found in atom but not in particle

Polymorphism in Fortran 2003



- ▶ Consider the case you have to evolve the position of a particle according to a given velocity field
 - ▶ atoms or ions may behave in the (nearly) same way wrt this evolution
 - ▶ and you do not want to write two (nearly) identical procedures for the two types
- ▶ Polymorphic procedures are the right way
 - ▶ i.e., procedures which can take one or more polymorphic variables as arguments
 - ▶ “polymorphic variable” = variable whose data type is dynamic at runtime
 - ▶ the **class** keyword allows F2003 programmers to create polymorphic variables
 - ▶ use it for dummy arguments (the simplest usage, not the only one)



```

subroutine setMass(p, m)
class(particle) :: p
real, intent(in) :: m
p%mass = m
end subroutine setMass
  
```

- ▶ The **p** dummy argument is polymorphic, based on the usage of **class(particle)**
- ▶ The subroutine can operate on objects that satisfy the "is a" particle relationship
 - ▶ **setMass** can be called passing a particle, atom, ion, or any future type extension of particle

```

type(particle) :: pa    ! declare an instance of particle
type(atom)      :: at    ! declare an instance of atom
type(ion)       :: io    ! declare an instance of ion
  
```

```

call setMass(pa, mm)    ! set the mass for a particle
call setMass(at, mm)    ! set the mass for an atom
call setMass(io, mm)    ! set the mass for a ion
  
```



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Selecting type



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- ▶ To access the components of the dynamic type, the **select type** construct is required
 - ▶ and optional arguments come in handy

Selecting type



```

subroutine initialize(p, mm, rr, vv, aan, ccharge)
class(particle) :: p
real :: mm
type(position) :: rr
type(velocity) :: vv
integer, optional :: aan, ccharge
p%mass = mm
p%r = rr
p%v = vv
select type (p)
type is (particle)
    ! no further initialization required
class is (atom) ! atom or extensions (except ion)
    if (present(aan)) then
        p%an = aan
    else
        p%an = 1
    endif
class is (ion) ! ion or extensions
    if (present(aan)) then
        p%an = aan
    else
        p%an = 1
    endif
    if (present(ccharge)) then
        p%charge = ccharge
    else
        p%charge = 0
    endif
class default ! give error for unexpected/unsupported type
    stop 'initialize: unexpected type for p object!'
end select
end subroutine initialize
    
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 - ▶ **type is**: satisfied if the dynamic type of the object is the same as the type specified in parentheses
 - ▶ **class is**: satisfied if the dynamic type of the object is the same or an extension of the specified type in parentheses

Selecting type



```

subroutine initialize(p, mm, rr, vv, aan, ccharge)
class(particle) :: p
real :: mm
type(position) :: rr
type(velocity) :: vv
integer, optional :: aan, ccharge
p%mass = mm
p%r = rr
p%v = vv
select type (p)
type is (particle)
    ! no further initialization required
class is (atom) ! atom or extensions (except ion)
    if (present(aan)) then
        p%an = aan
    else
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    endif
class is (ion) ! ion or extensions
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        p%an = aan
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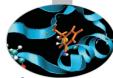


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 - ▶ **class is**: satisfied if the dynamic type of the object is the same or an extension of the specified type in parentheses
- ▶ Best practice: add a **class default** branch and print error when p is not an extension of **particle** type
 - ▶ an empty **type is (particle)** branch may be required to avoid getting error when p is only a particle

Selecting type



```
subroutine initialize(p, mm, rr, vv, aan, ccharge)
class(particle) :: p
real :: mm
type(position) :: rr
type(velocity) :: vv
integer, optional :: aan, ccharge
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p%r = rr
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select type (p)
type is (particle)
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    if (present(aan)) then
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    endif
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        p%charge = 0
    endif
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```



- ▶ Objects in Fortran 2003
 - ▶ A Fortran 90/95 module can be viewed as an object because it can encapsulate both data and procedures
 - ▶ But, derived types in F2003 are considered objects because they now can encapsulate data as well as procedures
 - ▶ Modules and types work together...
- ▶ Procedures encapsulated in a derived type are called type-bound procedures (“methods” in OO jargon)

```

type particle
  type(position) :: r
  type(velocity) :: v
  real :: mass
  contains
    procedure :: initialize => initialize_particle
end type particle
  
```

- ▶ **initialize_particle** is the name of the underlying procedure to be implemented
- ▶ Explicit interface is required: wrap in a module!



► Employing modules and types to design objects

```

module particle_mod
  type particle
    type(position) :: r
    type(velocity) :: v
    real :: mass
  contains
    procedure :: initialize => initialize_particle
  end type particle
  type, extends(particle) :: atom
  ...
  end type atom
  type, extends(atom) :: ion
  ...
  end type ion
contains
  ! insert the implementation or at least the interface of initialize_particle
  subroutine initialize_particle(p, mm, rr, vv, aan, ccharge)
    class(particle) :: p
    ...
    end subroutine initialize_particle
end module particle_mod
  
```



- **`initialize`** is the name to be used to invoke the type bound procedure

```

use particle_mod
type(particle) :: p           ! declare an instance of particle
call p%initialize(mas, pos, vel) ! initialize particle
  
```

- What about the first dummy argument of **`initialize`**?
 - it is known as the *passed-object* dummy argument
 - must be declared **`class`** and of the same type as the derived type that defined the type-bound procedure
 - by default, it is the first dummy argument in the type-bound procedure: it receives the object that invoked the type-bound procedure
- It is possible to pass another argument in place of the first one

```
procedure, pass(p) :: initialize
```

- ...or to avoid passing it at all

```
procedure, nopass :: initialize
```



- ▶ A child type inherits or reuses components from their parent or ancestor types: this applies to both data and procedures

```

type(particle) :: pa           ! declare an instance of particle
type(atom)      :: at         ! declare an instance of atom
type(ion)       :: io         ! declare an instance of ion
call pa%initialize(mas, pos, vel) ! initialize a particle
call at%initialize(mas, pos, vel, anu) ! initialize an atom
call io%initialize(mas, pos, vel, anu, cha) ! initialize a ion
  
```

- ▶ **initialize** behaves accordingly to the passed arguments, i.e. using **optional** and **select type** features
- ▶ Sometimes, another approach may be more appropriate: overriding!

Overriding TBP

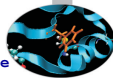


```

module particle_mod
  type particle
    type(position) :: r
    type(velocity) :: v
    real :: mass
    contains
      procedure :: initialize => initialize_particle
  end type particle
  type, extends(particle) :: atom
  ...
  contains
    procedure :: initialize => initialize_atom
  end type atom
  type, extends(atom) :: ion
  ...
  end type ion
  contains
    ! insert the implementation or at least the interface of initialize
    subroutine initialize_particle(p, mm, rr, vv, aan, cch)
    class(particle) :: p
    ...
  end subroutine initialize_particle
  subroutine initialize_atom(p, mm, rr, vv, aan, cch)
  class(atom) :: p
  ...
  end subroutine initialize_atom
end module particle_mod

```


Override with care

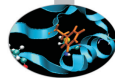


```

type(particle) :: pa           ! declare an instance of particle
type(atom)      :: at         ! declare an instance of atom
type(ion)       :: io         ! declare an instance of ion
call pa%initialize(mas, pos, vel) ! calls initialize_particle
call at%initialize(mas, pos, vel, anu) ! calls initialize_atom
call io%initialize(mas, pos, vel, anu, cha) ! calls initialize_atom
  
```

- ▶ Beware: an overriding type-bound procedure must have exactly the same interface as the overridden procedure except for the passed-object dummy argument which must be **class(new-type)**
 - ▶ optional arguments may hide useless arguments

Overriding TBP

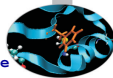


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    real :: mass
    contains
      procedure :: initialize => initialize_particle
  end type particle
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  ...
  contains
    procedure :: initialize => initialize_atom
  end type atom
  type, extends(atom) :: ion
  ...
end type ion
contains
  ! insert the implementation or at least the interface of initialize
  subroutine initialize_particle(p, mm, rr, vv, aan, cch)
  class(particle) :: p
  ...
end subroutine initialize_particle
  subroutine initialize_atom(p, mm, rr, vv, aan, cch)
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  ...
end subroutine initialize_atom
end module particle_mod

```

Override with care

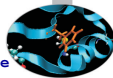


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- ▶ Of course, it is still possible to explicitly invoke the version defined by a parent type instead of the overridden one

Override with care



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- ▶ Beware: an overriding type-bound procedure must have exactly the same interface as the overridden procedure except for the passed-object dummy argument which must be **class(new-type)**
 - ▶ optional arguments may hide useless arguments
- ▶ Of course, it is still possible to explicitly invoke the version defined by a parent type instead of the overridden one
- ▶ And it is possible to prevent any type extensions from overriding a particular type-bound procedure

```
procedure, non_overridable :: initialize
```



- ▶ Information hiding allows the programmer to view an object and its procedures as a “black box”
 - ▶ procedure overriding is a first example of information hiding, **initialize** has different “hidden” implementations depending on the calling object



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 - ▶ safer against data corruption: the user may modify data only through adequate procedures
 - ▶ changes to the data structure will not affect codes using our class provided that we don't change interfaces



- ▶ Information hiding allows the programmer to view an object and its procedures as a “black box”
 - ▶ procedure overriding is a first example of information hiding, **initialize** has different “hidden” implementations depending on the calling object
- ▶ Hiding data:
 - ▶ safer against data corruption: the user may modify data only through adequate procedures
 - ▶ changes to the data structure will not affect codes using our class provided that we don't change interfaces
- ▶ Hiding procedures: e.g., prevent users from calling low-level procedures

public and private



- ▶ Fortran 2003 adds “private” and “public” keywords for derived types
 - ▶ beware of the placement of the keywords, in modules and/or in types: confused?

```

module particle_mod
  private ! hide the implementation of type-bound procedures
  public :: average_position_particle ! allow access to particle averaging position
  type, public :: particle
    private ! hide the data underlying details
    type(position) :: r
    type(velocity) :: v
    real :: mass
  contains
    private ! hide the type bound procedures by default
    procedure :: check_init => check_init_particle ! private type-bound procedure
    procedure, public :: initialize => initialize_particle ! allow access to TBP
  end type particle
  contains
    ! implementation of type-bound procedures
    subroutine initialize_particle(p, mm, rr, vv, aan, cch)
    ...

    subroutine check_init_particle(p)
    ...

    subroutine average_position_particle(p1,p2)
    class(particle) :: p1, p2
    ...
  end subroutine average_position_particle
end module particle_mod

```




- ▶ Data Polymorphism:
 - ▶ as how polymorphic dummy arguments form the basis to procedure polymorphism...
 - ▶ ...polymorphic non-dummy variables form the basis to data polymorphism



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 - ▶ you may encounter `class(*)`
- ▶ Generic-type bound procedures
 - ▶ like generic interfaces, but for type-bound procedures
- ▶ Abstract types and deferred bindings
- ▶ Finalization



Managing Memory

Extending the Language

- Derived Types

- Operators Overloading

- Parameterized Types

- Extending Types, and Objects

- Sketchy Ideas on Data Structures**

Bridging the Gap with C

Conclusions

A Recurrent Issue: SoA or AoS



```

► type flow
  real(rk) :: u(NX,NY,NZ)
  real(rk) :: v(NX,NY,NZ)
  real(rk) :: w(NX,NY,NZ)
  real(rk) :: p(NX,NY,NZ)
end type
  
```

```

type(flow) :: f
  
```

Or

```

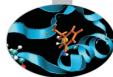
type flow
  real(rk) :: u,v,w,p
end type
  
```

```

type(flow) :: f(NX,NY,NZ)
  
```

Which one is best?

A Recurrent Issue: SoA or AoS



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► type flow
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end type
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type(flow) :: f
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Or

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type flow
  real(rk) :: u,v,w,p
end type
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```
type(flow) :: f(NX,NY,NZ)
```

Which one is best?

► Both have merits

A Recurrent Issue: SoA or AoS



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  real(rk) :: u(NX,NY,NZ)
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  real(rk) :: p(NX,NY,NZ)
end type
  
```

```

type(flow) :: f
or
  
```

```

type flow
  real(rk) :: u,v,w,p
end type
  
```

```

type(flow) :: f(NX,NY,NZ)
  
```

Which one is best?

- Both have merits
- The choice strongly depends on the computer architecture

A Recurrent Issue: SoA or AoS



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► type flow
  real(rk) :: u(NX,NY,NZ)
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  real(rk) :: p(NX,NY,NZ)
end type
  
```

```

type(flow) :: f
  
```

Or

```

type flow
  real(rk) :: u,v,w,p
end type
  
```

```

type(flow) :: f(NX,NY,NZ)
  
```

Which one is best?

- Both have merits
- The choice strongly depends on the computer architecture
 - for cache-based CPUs the choice is difficult (it depends on the order of the accesses of your numerical scheme)

A Recurrent Issue: SoA or AoS



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end type
  
```

```

type(flow) :: f
or
  
```

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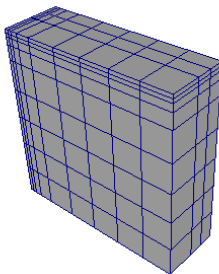
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  real(rk) :: u,v,w,p
end type
  
```

```

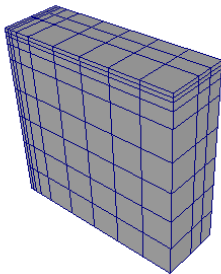
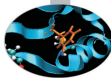
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```

Which one is best?

- ▶ Both have merits
- ▶ The choice strongly depends on the computer architecture
 - ▶ for cache-based CPUs the choice is difficult (it depends on the order of the accesses of your numerical scheme)
 - ▶ but using GPUs or MICs the first one is usually better!



- Let's imagine we have to solve a PDE



- ▶ Let's imagine we have to solve a PDE
- ▶ On a dense, Cartesian, non uniform grid
 - ▶ Mesh axes are parallel to coordinate ones
 - ▶ Steps along each direction differ in size from point to point

Keeping Information Together



```

type nonuniform_grid
  integer :: nx, ny, nz
  ! Grid steps
  real(rk), dimension(:), allocatable :: deltax
  real(rk), dimension(:), allocatable :: deltay
  real(rk), dimension(:), allocatable :: deltaz
end type
!...
type(nonuniform_grid) :: my_grid
integer :: alloc_stat
!...
allocate(my_grid%deltax(nx),my_grid%deltay(ny), &
         my_grid%deltaz(nz), STAT=alloc_stat)
if (alloc_stat > 0) then
  ! graceful failure
end if

```

- Related information is best kept together

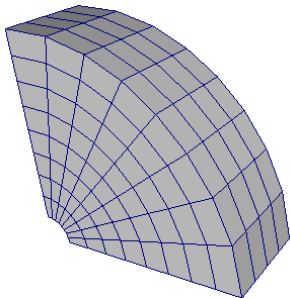
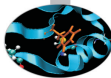


```

type nonuniform_grid
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!...
type(nonuniform_grid) :: my_grid
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!...
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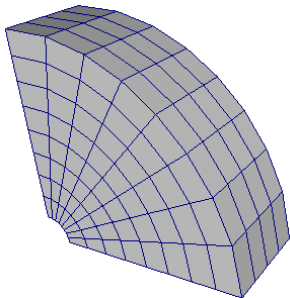
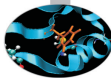
- ▶ Related information is best kept together
- ▶ Grid size and grid steps are related information

Structured Grids in General Form



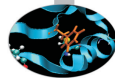
- Let's imagine we have to solve a PDE

Structured Grids in General Form



- ▶ Let's imagine we have to solve a PDE
- ▶ On a dense structured mesh
 - ▶ Could be continuously morphed to a Cartesian grid
 - ▶ Need to know coordinates of each mesh point

Sketching a Mesh Description



```

type meshpoint
  real(rk) :: x, y, z
end type

type, extends(meshpoint) :: normal
end type

type mesh
  integer :: nx, ny, nz

  type(meshpoint), dimension(:,:,:), allocatable :: coords

  type(normal), dimension(:,:,:), allocatable :: xnormals
  type(normal), dimension(:,:,:), allocatable :: ynormals
  type(normal), dimension(:,:,:), allocatable :: znormals

  real(rk), dimension(:,:,:), allocatable :: volumes
end type
!...
type(mesh) :: my_mesh

! allocate my_mesh components with extents nx, ny, nz
! immediately checking for failures!
  
```

A Recurrent Issue, Again



```
► real(rk) :: x(NX,NY,NZ)
   real(rk) :: y(NX,NY,NZ)
   real(rk) :: z(NX,NY,NZ)
```

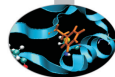
Or

```
type meshpoint
  real(rk) :: x, y, z
end type
```

```
type(meshpoint), dimension(NX,NY,NZ) :: coords
```

Which one is best?

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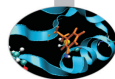
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Which one is best?

- Again, both have merits
 - The former (if done properly) allows hardware to play efficient tricks in memory accesses

A Recurrent Issue, Again



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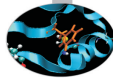
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type meshpoint
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type(meshpoint), dimension(NX,NY,NZ) :: coords
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Which one is best?

- Again, both have merits
 - The former (if done properly) allows hardware to play efficient tricks in memory accesses
 - The latter brings in cache all values related to a grid point as soon as one component is accessed

A Recurrent Issue, Again



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Which one is best?

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- Here, we lean to the latter

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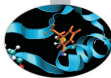
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 - ▶ The former (if done properly) allows hardware to play efficient tricks in memory accesses
 - ▶ The latter brings in cache all values related to a grid point as soon as one component is accessed
- ▶ Here, we lean to the latter
 - ▶ As in most numerical schemes, x , y , and z components of the same mesh point are accessed together

Multiblock Meshes and More



- A multiblock mesh is an assembly of connected structured meshes

Multiblock Meshes and More



- ▶ A multiblock mesh is an assembly of connected structured meshes
 - ▶ You could dynamically allocate a **mesh** array
 - ▶ Or build a **block** type including a **mesh** and connectivity information

Multiblock Meshes and More



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- ▶ Adaptive Mesh Refinement
 - ▶ You want your blocks resolution to adapt to dynamical behavior of PDE solution
 - ▶ Which means splitting blocks to substitute part of them with more resolved meshes

Multiblock Meshes and More

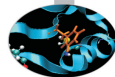


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 - ▶ Which means splitting blocks to substitute part of them with more resolved meshes
- ▶ Eventually, you'll need more advanced data structures



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 - ▶ Or build a **block** type including a **mesh** and connectivity information
- ▶ Adaptive Mesh Refinement
 - ▶ You want your blocks resolution to adapt to dynamical behavior of PDE solution
 - ▶ Which means splitting blocks to substitute part of them with more resolved meshes
- ▶ Eventually, you'll need more advanced data structures
 - ▶ Like lists
 - ▶ Like binary trees, oct-trees, n-ary trees

If You Read Code Like This...



```
type block_item
  type(block), pointer :: this_block

  type(block_item), pointer :: next
end type

!...
do while (associated(p))
  call advance_block_in_time(p%this_block)
  p => p%next
end do
```


If You Read Code Like This...



```

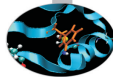
type block_item
  type(block), pointer :: this_block

  type(block_item), pointer :: next
end type

!...
do while (associated(p))
  call advance_block_in_time(p%this_block)
  p => p%next
end do
  
```

- ▶ It is processing a singly-linked list of mesh blocks
- ▶ You know how to handle it, now

And If You Read Code Like This...



```

type block_tree_node
  type(block), pointer :: this_block

  integer :: children_no
  type(block_tree_node), pointer :: childrens

  type(block_tree_node), pointer :: next_sibling
end type

!...
recursive subroutine tree_advance_in_time(n)
  type(block_tree_node) :: n
  type(block_tree_node), pointer :: p
  integer :: i

  p => n%childrens
  do i=0,n%children_no
    call tree_advance_in_time(p)
    p => p%next_sibling
  end do

  call advance_block_in_time(n%this_block)
end subroutine tree_advance_in_time

```

And If You Read Code Like This...



```
type block_tree_node
  type(block), pointer :: this_block

  integer :: children_no
  type(block_tree_node), pointer :: childrens

  type(block_tree_node), pointer :: next_sibling
end type

!...
recursive subroutine tree_advance_in_time(n)
  type(block_tree_node) :: n
  type(block_tree_node), pointer :: p
  integer :: i

  p => n%childrens
  do i=0,n%children_no
    call tree_advance_in_time(p)
    p => p%next_sibling
  end do

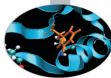
  call advance_block_in_time(n%this_block)
end subroutine tree_advance_in_time
```

- ▶ It is processing a tree of mesh blocks (AMR, probably)
- ▶ You need to learn more on abstract data structures
- ▶ Don't be afraid, it's not that difficult



- Write a program that:

Hands-on Session #3



- ▶ Write a program that:
 - ▶ reads an 'arbitrarily' long column of real numbers from an ASCII file



- ▶ Write a program that:
 - ▶ reads an 'arbitrarily' long column of real numbers from an ASCII file
 - ▶ store the values in a double-linked list

```
type line_list
  real :: a
  type(line_list), pointer :: next
  type(line_list), pointer :: previous
endtype line_list
```



- ▶ Write a program that:
 - ▶ reads an 'arbitrarily' long column of real numbers from an ASCII file
 - ▶ store the values in a double-linked list

```
type line_list
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  type(line_list), pointer :: next
  type(line_list), pointer :: previous
endtype line_list
```

- ▶ Start by declaring the first and current pointers

```
type(line_list), pointer :: first=>null(), current=>null()
```



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```
- ▶ Start by declaring the first and current pointers


```

      type(line_list), pointer :: first=>null(), current=>null()
      
```
- ▶ Next, allocate and initialize the **first** pointer


```

      allocate(first) ; first%next => null(); first%previous => null()
      current => first
      
```




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```

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- ▶ Next, allocate and initialize the **first** pointer

```

allocate(first) ; first%next => null(); first%previous => null()
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```

- ▶ Then loop over the lines of the file until a invalid read occurs
- ▶ For each valid read, add an element to the list and advance...



Managing Memory

Extending the Language

Bridging the Gap with C

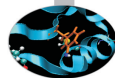
Conclusions

Mixing C and Fortran



- ▶ You may want to call a C function from a Fortran program
- ▶ Or call a Fortran procedure from a C program
- ▶ And you don't want to translate and re-debug
- ▶ Or you can't, as you don't have sources
- ▶ You may also want to share global data among C and Fortran program units
- ▶ This has been done in the past with non-standard tricks
- ▶ Fortran 2003 offers a better, standard way
- ▶ Let's look at it in steps

Two Naive Examples



- Imagine you have this C function:

```
double avg_var(int n, const double a[], double *var) {  
    double avg = 0.0;  
    double avg2 = 0.0;  
    for(int i=0;i<n;i++) {  
        avg += a[i];  
        avg2 += a[i]*a[i];  
    }  
    avg = avg/n;  
    *var = avg2/n - avg*avg;  
    return avg;  
}
```

and you want to call it from your Fortran code like:

```
avg = avg_var(m,b,var)
```



- Imagine you have this C function:

```
double avg_var(int n, const double a[], double *var) {
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    *var = avg2/n - avg*avg;
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}
```

and you want to call it from your Fortran code like:

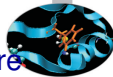
```
avg = avg_var(m,b,var)
```

- Or you have your favorite, thoroughly tested Poisson solver:

```
interface
    subroutine myPoissonSolver(l, m, n, f)
        integer, intent(in) :: l, m, n
        real(kind(1.0D0)), intent(inout) :: f(l,m,n)
    end subroutine myPoissonSolver
end interface
```

and you want to call it from your C code like:

```
myPoissonSolver(nx, ny, nz, field);
```



- ▶ We could think that Fortran interfaces and C declarations are enough
- ▶ And write, to call C from Fortran:

```

interface
  function avg_var(n, a, var)
    integer, intent(in) :: n
    real(kind(1.0D0)), intent(in) :: a(*)
    real(kind(1.0D0)), intent(out) :: var
    real(kind(1.0D0)) :: avg_var
  end function avg_var
end interface
  
```

- ▶ And to call Fortran from C, add on Fortran side:

```

interface
  subroutine myPoissonSolver(l, m, n, f)
    integer, intent(in) :: l, m, n
    real(kind(1.0D0)), intent(inout) :: f(l,m,n)
  end subroutine myPoissonSolver
end interface
  
```

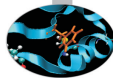
and on the C side, the declaration:

```
void myPoissonSolver(int nx, int ny, int nz, field[nz][ny][nx]);
```

- ▶ This is the right track, but still half way from our destination

Thou Shalt Not Mangle Names

- ▶ Fortran compilers mangle procedure names
 - ▶ All uppercase or all lowercase
 - ▶ Compilers may append/prepend one or two _ characters
 - ▶ And for module procedures is even worse
 - ▶ Used to be sorted out on the C side, in non-portable ways

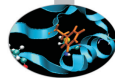


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- ▶ Enter Fortran 2003 **bind** attribute

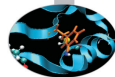
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- ▶ Enter Fortran 2003 `bind` attribute
- ▶ For C to Fortran:

```
interface
  function avg_var(n, a, var) bind(c)
    integer, intent(in) :: n
    real(kind(1.0D0)), intent(in) :: a(*)
    real(kind(1.0D0)), intent(out) :: var
    real(kind(1.0D0)) :: avg_var
  end function avg_var
end interface
```

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- ▶ For Fortran to C, Fortran side:

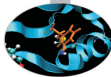
```
interface
  subroutine myPoissonSolver(l, m, n, f) bind(c)
    integer, intent(in) :: l, m, n
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end interface
```

and on the C side, the declaration:

```
void myPoissonSolver(int nx, int ny, int nz, field[nz][ny][nx]);
```

Thou Shalt Care for Argument Passing

- ▶ Fortran passes arguments by reference
 - ▶ Under the hood, it's like a C pointer
 - ▶ Works for C arrays and pointers to scalar variables
 - ▶ But usually scalars are passed by value in C



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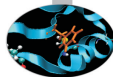
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interface
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```

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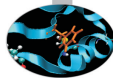
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```

and on the C side, still the declaration:

```
void myPoissonSolver(int nx, int ny, int nz, field[nz][ny][nx]);
```

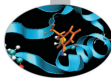
Thou Shalt Care for Data Size and Layout

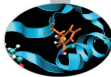
- ▶ Fortran is quite liberal on data sizes
 - ▶ Implementations have a lot of freedom
 - ▶ And C is also quite liberal



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- ▶ For C to Fortran:

```
interface
  function avg_var(n, a, var) bind(c)
    use iso_c_binding
    integer(c_int), value :: n
    real(c_double), intent(in) :: a(*)
    real(c_double), intent(out) :: var
    real(c_double) :: avg_var
  end function avg_var
end interface
```

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- ▶ For Fortran to C, Fortran side:

```
interface
  subroutine myPoissonSolver(l, m, n, f) bind(c)
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end interface
```

and on the C side, still the declaration:

```
void myPoissonSolver(int nx, int ny, int nz, field[nz][ny][nx]);
```

More from `iso_c_binding`



- ▶ **`iso_c_binding`** defines named constants holding kind type parameter values for intrinsic types for the platform
- ▶ **`integer(c_int)`** is the kind value corresponding to a C `int`
- ▶ Negative values are used for unsupported C types, so the compiler will flag the problem

- ▶ A few of them:

Type	Kind	C type
integer	<code>c_int</code>	<code>int</code>
	<code>c_short</code>	<code>short int</code>
real	<code>c_float</code>	<code>float</code>
	<code>c_double</code>	<code>double</code>
complex	<code>c_float_complex</code>	<code>float _Complex</code>
	<code>c_double_complex</code>	<code>double _Complex</code>
logical	<code>c_bool</code>	<code>_Bool</code>
character	<code>c_char</code>	<code>char</code>

- ▶ Fortran 2008 adds **`c_sizeof()`**, check with your compiler!

Mapping Arrays



- ▶ Fortran has multidimensional arrays
- ▶ C has arrays of arrays (of arrays...)
- ▶ Thus the mapping of array indexes to actual data layout in memory is inverted
 - ▶ Fortran array **a** (**L**, **M**, **N**)
 - ▶ maps to C array **a** [**N**] [**M**] [**L**]



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 - ▶ C array parameter **a** [**]**
 - ▶ maps to Fortran assumed size array parameter **a** (*****)
- ▶ In C99, Variable Length Arrays were introduced
 - ▶ C99 array parameter **a** [**nz**] [**ny**] [**nx**]
 - ▶ maps to Fortran array parameter **a** (**nx**, **ny**, **nz**)

Derived Types and Global Data



- **bind** also helps for derived types and global data
- For derived types, each component must be interoperable

Fortran

```

type, bind(c) :: particle
  integer(c_int) :: n
  real(c_float) :: x,y,z
  real(c_float) :: vx,vy,vz
end type particle
  
```

C

```

typedef struct particle {
  int n;
  float x,y,z;
  float vx,vy,vz;
} particle;
  
```

- For module variables or common blocks, use

Fortran

```

integer(c_long), bind(c) :: n

real(c_double) :: m,k
common /com_mk/ m,k
bind(c) :: /com_mk/
  
```

C

```

extern long n;

extern struct mk {
  double m, k;
} com_mk;
  
```

- Note: common blocks become C **structs**

Fortran Pointers vs. C Pointers



- ▶ As of argument passing, not a problem
- ▶ But Fortran pointers are not interoperable with C
- ▶ Fortran pointers sport richer semantics, notably:
 - ▶ multidimensional arrays
 - ▶ non-contiguous memory areas
- ▶ C functions returning a pointer must have `type(c_ptr)` type (from `iso_c_binding`)
- ▶ Ditto for C pointer variables and pointer members of C `structs`:

Fortran

```

type, bind(c) :: block
  integer(c_int) :: n_neighbors
  type(c_ptr)   :: neighbors
  type(c_ptr)   :: grid
end type block
  
```

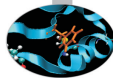
C

```

typedef struct {
  int n_neighbors;
  int *neighbors;
  mesh *grid;
} block;
  
```

Translating Pointers Back and Forth

- **iso_c_binding** module provides much needed help



Translating Pointers Back and Forth



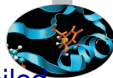
- ▶ **iso_c_binding** module provides much needed help
- ▶ **c_loc(*x*)** returns a valid C pointer to the content of variable *x*
- ▶ **c_f_pointer(*cptr*, *fptr*[, *shape*])** performs the opposite translation, writing the result in the Fortran pointer *fptr*
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 - ▶ An optional *shape* argument like (/n/) or (/1,m,n/) gives it a shape for array pointers
- ▶ If **f_proc** is an interoperable Fortran procedure, **c_funloc(f_proc)** returns a valid C pointer (**type(c_funptr)**) to it
- ▶ **c_f_procpointer(*cfptr*, *fpptr*)** performs the opposite translation, writing the result in the Fortran procedure pointer *fpptr*

Thou Shalt Compile and Link Properly

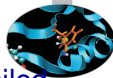


- Obviously, C and Fortran sources must be separately compiled and then linked

```
user@cineca$> gcc -c fun_cmd.c
user@cineca$> gfortran -c main_cmd.f90
user@cineca$> gfortran fun_cmd.o main_cmd.o -o main_cmd
```

- Easy, if calling C functions from a Fortran program
 - Fortran Runtime Library is usually built on top of C one

Thou Shalt Compile and Link Properly



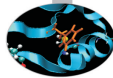
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```

- ▶ Easy, if calling C functions from a Fortran program
 - ▶ Fortran Runtime Library is usually built on top of C one
- ▶ Less so if calling Fortran procedures from a C program
 - ▶ Fortran compiler might insert calls to its Runtime Library
- ▶ Best practice:

```
user@cineca$> gcc -lgfortran procedures.o main.c
```

- ▶ Your mileage may vary, browse your compiler manuals



► Write the Fortran interface to C `qsort`

```

module qsort_c_to_fortran
  use iso_c_binding
  integer, parameter :: sp = kind(1.0)
  interface
    !Write the Fortran interface to C qsort!
    !void qsort(void *base,
    ! size_t nmemb,
    ! size_t size,
    ! int (*compar)(const void *,const void *));
  end interface
contains
  function compare_reals(a,b) bind(c)
    integer(c_int) :: compare_reals
    real(c_float) :: a,b
    if(a>b) then
      compare_reals=1
    else if(a<b) then
      compare_reals=-1
    else
      compare_reals=0
    endif
  end function compare_reals
end module qsort_c_to_fortran

```

```

program test_qsort_c
  use qsort_c_to_fortran

  integer(c_size_t), parameter :: n=7
  real(c_float), pointer :: a(:)

  allocate(a(n))
  call random_number(a)
  print*, 'Unordered a: '
  print*, a

  call qsort(c_loc(a(1)), n, c_sizeof(a(1)), &
    c_funloc(compare_reals));

  print*, 'Ordered a: '
  print*, a

end program test_qsort_c

```



Managing Memory

Extending the Language

Bridging the Gap with C

Conclusions



- ▶ More Fortran practice
 - ▶ Time was tight, and that's your job

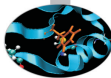


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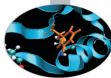


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- ▶ More Fortran
 - ▶ Full object oriented programming
 - ▶ Floating point environment
 - ▶ Direct I/O
 - ▶ Asynchronous I/O
 - ▶ Submodules
 - ▶ Even more format edit descriptors
 - ▶ A few more statements and quite a few intrinsics
 - ▶ Coarrays

Looking for More



-  J3 US Fortran Standards Committee
<http://www.j3-fortran.org/>
-  ISO WG5 Committee
<http://www.nag.co.uk/sc22wg5/>
-  Fortran 2003 Standard Final Draft
Search Internet for n3661.pdf
-  Fortran Wiki
<http://fortranwiki.org/>
-  M. Metcalf, J. Reid, M. Cohen
Fortran 95/2003 Explained
Oxford University Press, corrected ed., 2008
-  M. Metcalf, J. Reid, M. Cohen
Modern Fortran Explained
Oxford University Press, 2011
-  S. Chapman
Fortran 95/2003 for Scientists & Engineers
McGraw-Hill, 3d ed., 2007
-  Adams, J.C., Brainerd, W.S., Hendrickson, R.A., Maine, R.E., Martin, J.T., Smith, B.T.
The Fortran 2003 Handbook
Springer, 2009



Salvatore Filippone's Home Page

www.ce.uniroma2.it/people/filippone.html



Parallel Sparse Basic Linear Algebra Subroutines

www.ce.uniroma2.it/psblas/index.html



Numerical Engine (for) Multiphysics Operators

www.ce.uniroma2.it/nemo/index.html



Portable Fortran Interfaces to the Trilinos C++ Package

trilinos.sandia.gov/packages/fortrilinos/



Stefano Toninel

*Development of a New Parallel Code for Computational Continuum Mechanics
Using Object-Oriented Techniques*

PhD Thesis, University of Bologna, 2006.



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