Software Design and Development

Checking and Diagnostics

Nick Maclaren

nmm1@cam.ac.uk

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Summary

This covers the most useful coding techniques
How you can make your code largely self–checking

- It's not always possible to use debuggers
Don't always work under schedulers, MPI etc.
Can almost always use these methods

- They are all suitable for use in production code
Most research projects involve ongoing change

- You won't use all of them in every program
Remember that you have to use your judgement

Inserting Checking

- Lots of checks is sign of competence

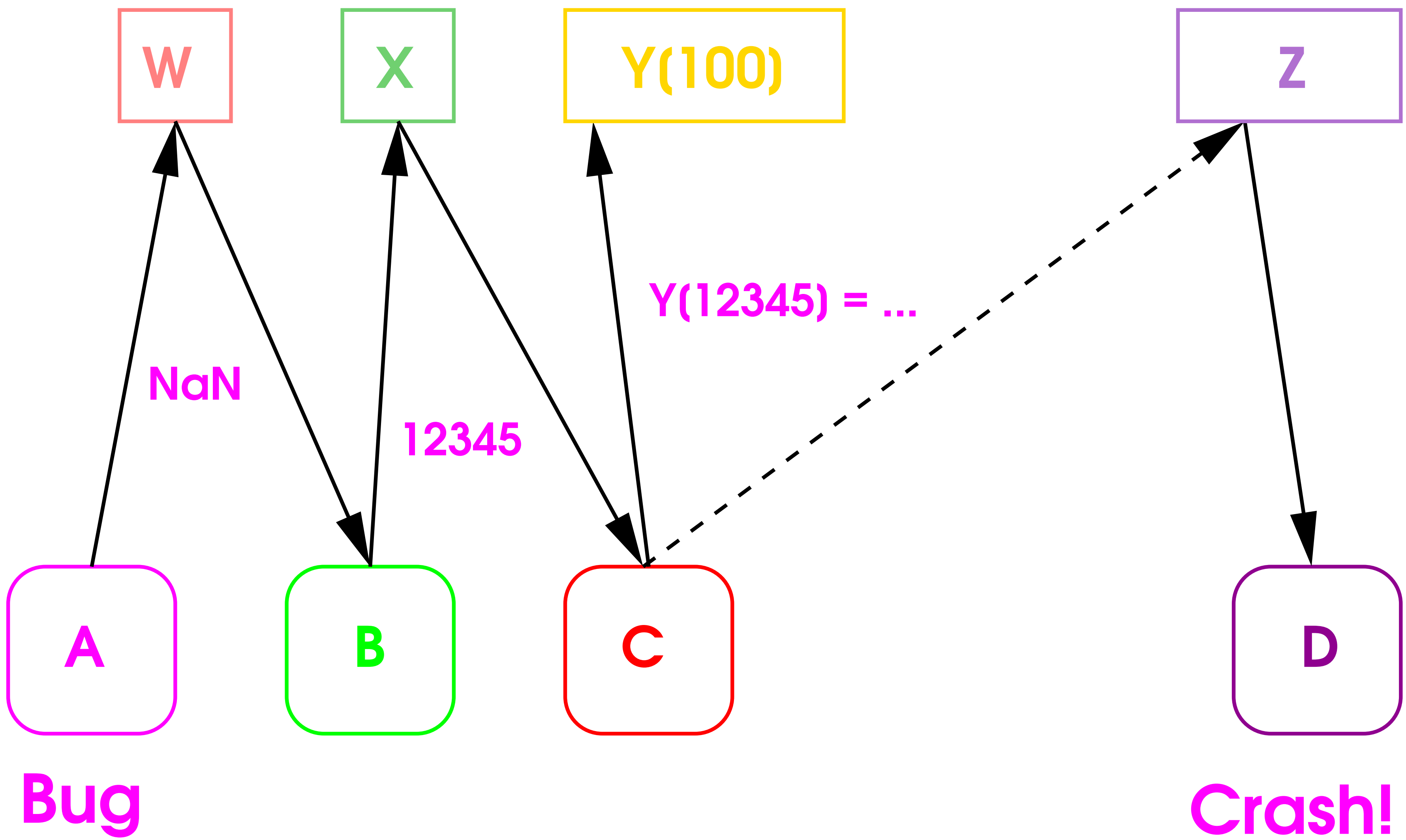
Check before use if cost is not too much
Will often pick up unexpected bugs – why?

Function A makes object W's value invalid
Function B uses W and mangles object X
Function C uses X and overflows array Y
Causes unrelated structure Z to be trashed
Much later function D uses Z and crashes

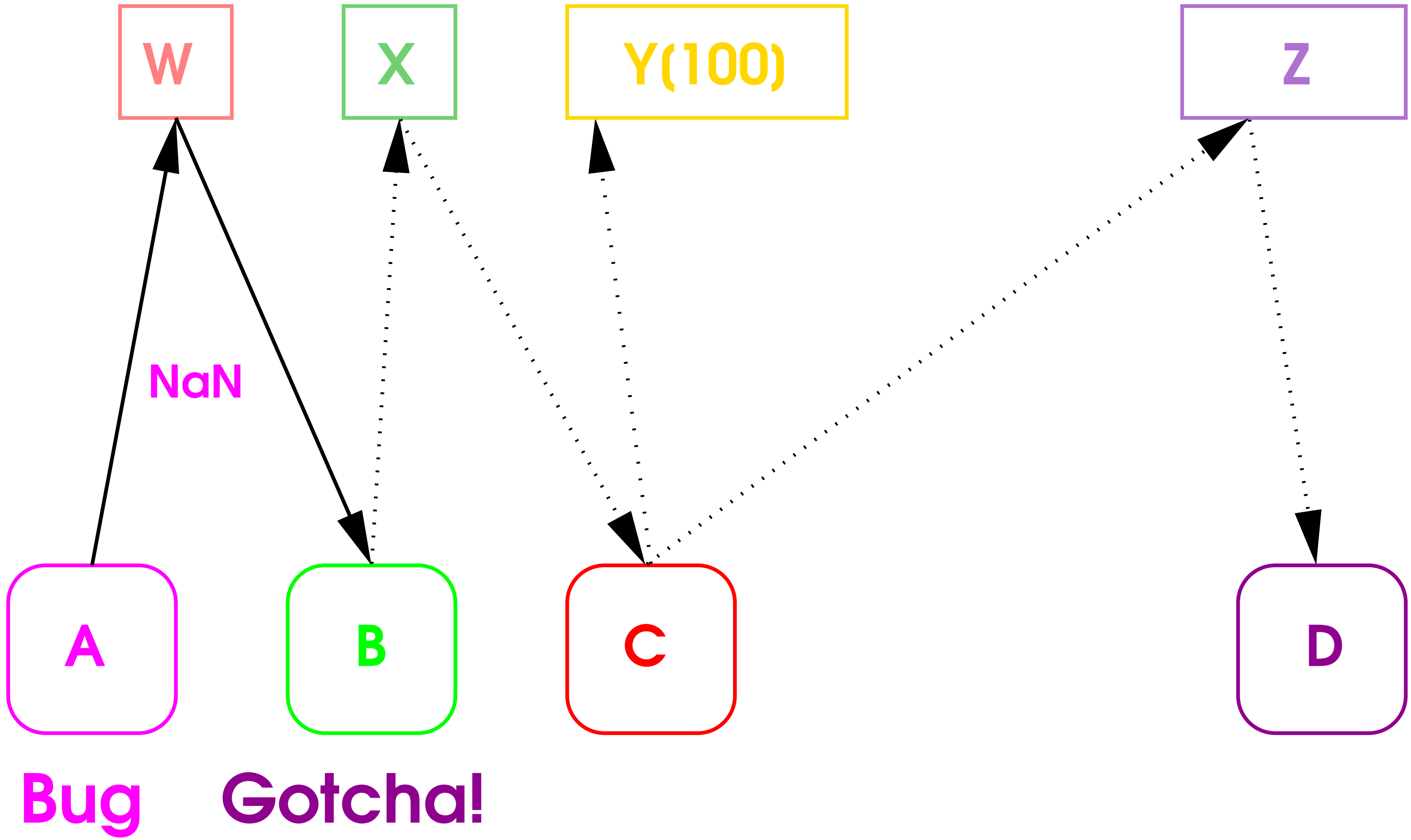
Checking X in B (or even C) catches AN error

- Hopefully before too much evidence lost!

Unchecked Bugs 'Creep'



Checking and Bug 'Creep'



Problem Movement

Worst common problems in many codes are:

- Invalid array indices and pointers
- Race conditions and related bugs
- Code bugs causing optimisation problems

All tend to disappear or change symptom easily

- ANY code change or compiler option difference

Including any changes due to the preprocessor use

⇒ Minimise recompilation for diagnostics
Even run–time environment changes can provoke this

Unpredictable Problems

Race conditions very common in parallel code
But there are many other fairly common causes

- May be probabilistic – same executable and data
Symptoms usually predictable, but may move around
Failure may be rare and occurs well into the run

- Worth doing a lot to avoid such problems arising
It's not easy to track down bugs statistically

Warning

> You might as well fall flat on your face as lean over too far backward.

James Thurber, “The Bear Who Let It Alone”

- Adding lots of checking code takes time

And checking code can itself include bugs
An optimum amount to maximise coding efficiency

A far higher proportion than most programs have
But it’s still possible to have too much

- Deciding the level is a matter of judgement

Numeric Errors

Things like overflow, division by zero, etc.
Very little is trapped and diagnosed nowadays
Often only integer division by zero

- You must do any checking yourself

Especially true for complex arithmetic

Untrapped numeric errors often cause logic errors
Untrapped logic errors often cause overwriting errors
Untrapped overwriting errors often cause crashes
Or, much worse, often cause nonsense output

Consequences

- Lots of random, simple checks is best
Few, perfect checks helps less with corruption

- Also helps when making changes later
Forget what you were assuming elsewhere?
Many of my errors like that fail on my checks

- Check value ranges, indices/bounds etc.
Check any consistency properties that you can
Often simple ones, like if $A < 0$ then $Y > 2$

Unit Testing

- Test each component before including it
Sometimes need to test several together
Much less confusing than testing whole program

- Remember to test error handling, at least roughly
Helps to avoid wasted time with later failures

- Won’t pick up all bugs – especially exceptions
Don’t assume that tested means bug–free

- Often useful to put components in libraries
Can include them in program or run a test on them

Test Suites

- Keep your test data and the output from it

Can rerun and check – known as regression testing

Same applies to unit test programs and data

When you make a significant change to your code

- Rerun appropriate regression tests and check

- Automated testing is a vast saving in effort

Not perfect, but can save a lot of manual debugging

Object Orientation

Will describe in terms of object–orientation

- That is an approach, not a dogma

The techniques are useful far more generally

- Object $\equiv$ coherent set of data

May be a collection of scalars and arrays

An object is often made up of sub–objects

- Use this structure to keep your code simple

E.g. don't duplicate code – call the next level
And use recursion if it matches your structure

Object Identification (1)

It is useful to tag each object with an identifier
Unix file formats use ‘magic numbers’ for this

```
#define WOMBAT_ID 3579138481
typedef struct {
        int id;        // Always WOMBAT_ID
        ...
} wombat;
```

- An unlikely value (usually text or integer)

Use for checking a pointer refers to right type
Also very useful when using an interactive debugger

Object Identification (2)

- Obviously, needs to be in a known location
Simplest to put at very start of structure

- Very useful for C/C++ – less so in Fortran
The less type safe the language, the more useful

This can be useful for RDMA and MPI buffers:

```
typedef struct {
        char[8];            // Always "Wombat"
        uintptr_t hash;          // (&object)^HASH_CODE
        ...
} wombat;
```

Initialisation (1)

- Almost always initialise explicitly

Not just static data, but stack and allocated

- Don't trust automatic clearing to zero

Standards don't say what most people think they do

- No, it's not too expensive!

Cost is only linear – use is usually much more

Use a 'constructor' to create 'objects'
Often does both allocation and initialisation
May initialise only for language−allocated objects

Initialisation (2)

- Best to use an invalid value if object is unset

Preferably one that causes a crash if used

- Better than unpredictably wrong results

Initialising to zero has its uses, though

Values like –1.23e300, –123456789 etc.
IEEE 754 NaN is useful for this, too

- Useful to vary value, to see if bugs move

Can use different values to flag history

Object Termination

Don’t forget to use an explicit ‘destructor’
Useful hook for checking and tracing

- Consider resetting contents to invalid on disuse

Last action before freeing data or returning
Very rarely done – but can be very useful

- Worthwhile mainly if code uses pointers

Your code may have one saved somewhere
Can be useful in some non–pointer codes

Huge Sparse Arrays

One case where initialisation dominates
GB–TB arrays with only (say) 1% used
Lazy way of making system do indexed lookup

- Absolute nightmare, in a great many ways

Can't use memory limits to trap runaway code
And sometimes systems allocate all the pages

- Doing it yourself is easy and more flexible

The caching can be tuned for the application
Ask for help if you need to do this

Enabling Diagnostics

- I don't love preprocessors much
Have to rebuild code to add diagnostics
Many nasty problems then move around

- Strongly recommend a run–time option
Can select the diagnostic level you want

Can make selectable by environment variable
Or by a program argument setting a flag
Or by whether a suitable file exists
Or by a command in the input, or . . .

Diagnostic Design (1)

- Typically needs a throughness parameter
E.g. bounds etc.; all values; cross–checks

- Useful for run–time option to set default
And to be able to override that in the call

- Exactly the same applies to tracing
May prefer a separate option for tracing

- Exactly the same applies to object display
Again, you may prefer a separate option

Diagnostic Design (2)

Minimum costs are then testing the option
This is a single, scalar, global, so efficient
Minimal C/C++ and Fortran examples of use are:

```
#include "diag.h"
if (diag_level > 0) check_object(diag_level, ...);
USE diag
IF (diag_level > 0) CALL check_object(diag_level, ...)
```

Can use C/C++ assert macro if you like
But you can do better yourself, very easily

Object Display (1)

- All objects should have a display primitive

Displays contents so that you can see what they are

Merely a convenience – but, oh!, how much!
Very useful with some debuggers – see later

- Typically needs a level parameter

Says how far to indirect in structured data
And how much of large arrays to display!

- Or have more than one primitive

Object Display (2)

- Remember not to assume object is correct
Very often want to display broken data

Should work if pointers are null or not allocated
Check indices and pointers for being in range
Assume any values, whether 'possible' or not

- May call it from the checker if that fails
Probably the most generally useful approach

Object Checking

- All objects should have a checking primitive
Answers “Is this object vaguely correct?”
E.g. values within limits, self–consistent

- Tedious to write, but incredibly useful
Can call automatically, or insert manually
Can call from many debuggers, too

- Design objects to be thoroughly checkable
Keep data clean, with checkable constraints
Make data redundant, maintain invariants

Automatic Use

- Generally call automatically, at least once

To ensure that checking code remains correct

Perhaps at end of initialisation, start of termination,
in error handlers, and . . .

- Strongly recommend adding a lot more calls

Most important reason for a run–time option

High for debugging, lower for production

- Hit a problem? Rerun with checking

Manual Use

- This is a very effective way of debugging

It's the way that I generally debug non–trivial code

- An object goes bad after 30 minutes running

Put checks where they will be called fairly often

- Now you know more precisely where things started

Find out why, add checks for that, and repeat

- Can often call procedures from debuggers

Calling checking procedures saves a lot of effort

Example

- dposv is LAPACK Cholesky solver

Example of checking arrays before and after:

```
call check_upper (n, a, lda)
call check_rect (n, nrhs, b, ldb)
call dposv ('u', n, nrhs, a, lda, b, ldb, info)
call check_upper (n, a, lda)
call check_rect (n, nrhs, b, ldb)
```

$O(n^3)$ calculation – $O(n^2)$ checking cost

Invariants

These are things that are always true
I.e. from after initialisation to before termination
Possibly except inside one of its methods

- If they are ever false, then something is wrong

Perhaps a logic error or perhaps overwriting

- Every invariant can be checked anywhere

Very useful to track down where things have failed

They can be programmatic – e.g. array indices
Or numeric – e.g. values have certain limits
Or things like an array must be positive definite

Checking Example

```
INTEGER :: used, index(size), j
REAL(FP) :: data(size)

IF (used < 1 .OR. used > SIZE) CALL Diag(...)

DO j = 1 , size
   IF (index(j) < 1 .OR. index(j) > size) CALL Diag(...)
END DO
```

First is basic check, can call everywhere
Second is linear in time, but more powerful

Using Invariants

Initialise all of INDEX to (say) −123456789
Initialise all of DATA to (say) −1.0e300 or NaN
Remember to reset the values on disuse

- Can now check valid values match USED

All before USED are good, all after are bad

- Will also detect some random overwriting

- Scalar invariants are generally more useful

Dirt cheap to check, and pick up many mistakes

- Create, maintain and use invariants when possible

Argument/Result Checking

Ideally, something like:

```
double operate (double array [ ], int size) {
    if (size <= 0 || size > MAXARRAY) fail(...);
    check_array(array,size);
    . . .
    result = . . .
    check_value(result);
    return result;
```

All major procedures should have some of this

Tracing

- Most common form is tracing control flow

Answers “How did we get? HERE?”

- Also events, data flow and state changes

I.e. “How did we get into THIS mess?”

Yes, the compiler/debugger should do this
But providing that is “Someone Else’s Problem”

Let’s start with simple function tracing

Fortran Example

```
FUNCTION Fred (X, Y, Z)
      USE Diagnose
      INTEGER :: Fred, x, y, z
      IF (diag_flag) CALL Diag ('Fred', 0)
            . . .
      IF (diag_flag) CALL Diag ('Fred', 1)
END FUNCTION Fred
```

Can add using a preprocessor (e.g. a Python script)

C/C++ Example

```
#define DIAG(X,Y) if (diag_flag) diag(x,y);

#include "diagnose.h"
int fred (int x, int y, int z) {
      DIAG ('fred', 0)
            . . .
      DIAG ('fred', 1)
}
```

Or can add in same way as for Fortran

What to Trace

Usually want critical argument and result data
E.g. identity of object being acted upon

- Details are entirely dependent on requirements

Might just be an object id (e.g. a index)
Might include some of the argument values
Might include a summary of the action
Might include anything else useful . . .

Controlling Tracing

- Best if diag_flag is a run–time option

Can enable and disable without recompiling

- Tracing can produce a lot of output

Usually trace to a file, not standard units

- May need to select type and level

E.g. file tracing: open/close, all control, all transfers
Or state changes: main ones, all changes, all uses

Remember, primarily what saves you most time

Don't Forget

- May be more than one return statement

Plus reaching end of procedure, of course
Remember setjmp/longjmp, try/catch/throw,
raise/abort/signal etc.

- Can flush file each time for safety

fflush in C/C++; FLUSH in Fortran
Or in C/C++: setvbuf(<file>,NULL,BUFSIZ,_IOLBF)

Crashes lose data otherwise – but can be slow
A case for having another run–time option
See later for another approach

What Do We Do Then?

- Could print entry and exit information

Do that to a file, as can be voluminous

Then is easy to write tool to display as tree
Or display a traceback or count calls, or . . .
There are often compiler options to do those
As they stand, they aren't very useful

But you can select on other data you printed
Look at just the calls relevant to specific problem

Storing The Data

- Can save active names (traceback) in array
A trivial example of using your own stack
This form needs pushback when functions return

- Now can write your own traceback function
Call when program hits a problem or is signalled

Very few compilers provide this – why not all?

But needn't trace returns – just keep last N calls
Gives a history of calls, which is also useful

Circular Trace Buffers

- To do this, use a circular trace buffer

Maintains last N calls, or calls and returns

VERY useful facility, little taught now
The most critical data, for fixed memory use

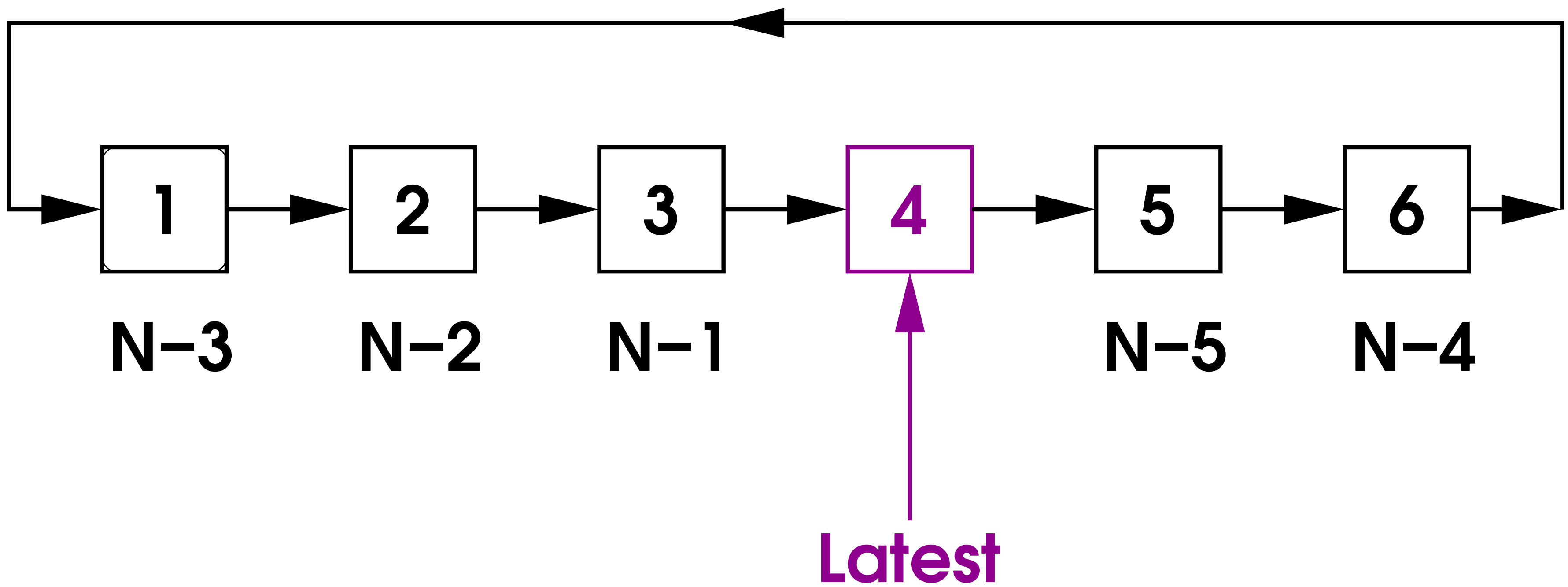
- Don't forget a function to display it

- Each buffer saves just one kind of trace data

Arbitrary number of buffers – often dozens

The notes have some code – it's very short

Circular Trace Buffers



C/C++ Example (1)

```
#define SIZE 3
static const char *names[SIZE];
static int actions[SIZE], entry = -1, looped = 0;

void trace (const char *name, int action) {
    if (++entry >= SIZE) {
        entry = 0;
        looped = 1;
    }
    names[entry] = name;
    actions[entry] = action;
}
```

C/C++ Example (2)

```
void display () {
    int n = entry;
    if (n < 0) return;
    while (1) {
        cerr << names[n] << "   " << actions[n] << endl;
        if (--n < 0) {
            if (! looped) return;
            n = SIZE-1;
        }
        if (n == entry) break;
    }
}
```

Event Tracing

- Tracing not restricted to function calls

Can trace any action, event or similar
Want to know order of actions or events

Trace changes or accesses to selected data
Or changes to state – program's or system

Can annotate trace with the context
E.g. component responsible for the change

For example, 'man mtrace' under Linux
Just a random example of use of technique

Methodologies

These are methodologies – not just tools
Techniques are much more general

- Always think “Should I automate this?”

Answer is often “infeasible” or “it’s not worth it”
But sometimes it can save massive effort

TANSTAAFL
There Ain’t No Such Thing As A Free Lunch
Automation costs time, but can save much more

Overheads

- Not all that much on a modern system
Depends on what the function actually does
I/O, data access costs; mere logic is cheap

- Example above is designed to be very cheap
If diag_flag is unset, drops through
Most hardware will predict that correctly

May be too expensive to do it for all calls
- Can omit from heavily used auxiliaries
Will still get most of the benefit

Using From Debuggers

Many debuggers can call program code

- No use if data are completely corrupt :–(

Calling many functions changes program state
But not checking, display and tracing functions
At least if you have coded them right!

- Makes use of debugger much more powerful

The Old Guard (who? me?) do that manually
It's irrelevant – you need the same primitives

Displaying Data Structures

- A real problem, however you do it
Scalars are easy, but arrays? And pointers?
How far down do you want to indirect?
Or do you want pointer values and target addresses?

No general solution, and debuggers don't help
Writing display functions is always tedious

- You can implement your own printf–imitation
Painful in Fortran – one call per argument

More Advanced Use

Much more on some advanced uses in notes

- You are not recommended to rush in

Use them when you need to, not in every program

Also, see notes for some related facilities

Tracing Global State

I said that global state is horrible
There's lots of it in C, C++, POSIX
Big problem if wrong at component boundary

Try tracing state and component changes
Best method of tracking this issue down

Biggest problem is instrumenting your code
It's trivial if you have encapsulated the actions

Handling Crashes

Often lose diagnostic output after crashes

- Can trap most signals and close files

Good libraries do that by default
Need a run–time option to get a dump, of course

Can also call traceback procedures in such a handler
Or can print out history or objects, or ...

- That may not work – but there was a crash anyway

Details are repulsive, but don't need to know them

Using In Test Suites

Often have suites of data used for testing
"Regression testing" checks old data still works

- But a lot of bugs get through

- And what when changes are to output?

Can't check results automatically any longer

Using good checking primitives helps a lot
Runs slower, but more confidence in result

- Still won't check answers are right

Using Tracing Hooks

- Tracing hooks allow use–counting or timing

Can select with just a run–time option

- Good place to insert checking code
- Or can call back to debugger

E.g. by calling trapped function or failing

Can enable when context is appropriate
1513th time fred $\Rightarrow$ joe $\Rightarrow$ alf

Long-Running Problems

- Most systems have a fairly small job time limit

For RAS, maintenance etc. – e.g. 24 or 48 hours

- A program may write its current state to a file

  [This is often called checkpointing]
- The job may resubmit another as it finishes

It starts by restoring from the checkpoint

- Best to use alternate checkpoint files

In case of a crash while it is being written

Make

make is a tool for managing program rebuilding
Recompiles all changed sources and only those
Many equivalent programs and derivatives

- Essential when file structure gets complicated
Saves a lot of build time – and reduces mistakes!
For a few files, a simple recompilation script is OK

Not covered in this course – but recommended
- Golden rule of makefiles: KISS
Complexity causes non–portability and bugs

Source/version/revision Control

CVS, subversion and a zillion others
Manage source code updates and variant versions
Usually allow archiving, roll–back etc.

Main alternative is disciplined file management
E.g. taking snapshots of source at intervals

- But they are essential if several developers

Manual coordination is extremely error prone

I don't like these, for a variety of reasons
Again, not covered in this course

Integrated Development Environments

Very often little more than snake oil
More kindly, a GUI toolkit for development

Often include version control (CVS etc.)
Plus integrated make equivalent

- Use them if you need to or like them

- But they WON'T help with debugging

Best ones provide regression testing etc.

- Nothing that you can't do with scripts

Syntax-Aware Editors

Popular bandwagon in 1980s – still here
Near–total waste of time and money
Who spends 50% of time fixing syntax errors?

Users on first programming course, that's who!
And, of course, senior executives and similar

- Experienced programmers spend ≈1%

Also make certain classes of error more common

What we need is run–time checking

- Cases of undefined (invalid) behaviour
- And, much worse, logical errors

Run-Time Checking

Some compilers and debuggers do a little
There may also be special tools
Intel has some tools for parallelism

Array bound & pointer checking is useful
Also uses of uninitialised data etc.
So is trapping of arithmetic errors

- All rare in Fortran, impossible in C/C++

Nothing available for logical errors

- No option but to include your own

General Rules

Enable all warnings and usually standard
You may use new system or compiler version

Always develop with full optimisation enabled
Debug only once and get more thorough analysis

Run–time check all options often run very slowly
Sometimes only factor of 3, sometimes more than 30

But try to test all code at least once with them
Generally useful only for Fortran, unfortunately

Compiler Options and Debugging

Arithmetic checking issues covered in lectures 3 and 4

Computer Arithmetic and Numerics
Some Common Numerical Issues

Languages etc. covered in lecture 5 and 6
Languages and Parallelism
Using Shared Memory Correctly and Efficiently

See notes for some related information

C/C++ Compiler Options (1)

Use gcc/g++ –O3 –Wall –Wextra –pedantic –ftrapv
preferably also –std=c99/c++11
Possibly –Wwrite–strings –Wshadow –Wcast–qual
and perhaps –Wconversion
And some experts recommend yet more . . .

They also now have a 'sanitizer' to instrument code
Try –fsanitize=undefined,address for debugging
Also for some pointer errors and more – see spec.

- gcc –g –O3 works properly!

You do not need to set –O0 to use –g

C/C++ Compiler Options (2)

- Also use other compilers if you have them

Different ones have different checking

For Intel use icc/icpc –O3 –debug all –w2 –ansi–alias
and –fp–trap divzero,invalid,overflow
preferably also –std=c99/c++11

Sun has –xcheck for stack overflow
Intel and others have something similar
Some have limited pre–initialisation

- That's more–or–less it, unfortunately

Restrictions on Checking

Despite claims, pick up only obvious errors
E.g. only addresses outside allocated objects
Not that simple, but too complicated to describe here

Run–time checking almost futile in C or C++
Is code a subtle error or extreme use?
Standards are seriously ambiguous and inconsistent

Applies to most array bound and pointer checks
Also integer overflow, due to signed/unsigned morass
And floating–point errors, due to IEEE 754

Fortran Compiler Options (1)

Ideally, convert old code to Fortran 90 or later
https://www-internal.lsc.phy.cam.ac.uk/nmm1/OldFortran/

Much better checking than Fortran 77
Assumed-shape arrays, explicit interfaces etc.

- Using multiple compilers still useful

Unexpected warnings often indicate a bug

Fortran Compiler Options (2)

NAG Fortran by far best run–time checking
Use nagfor –O3 –gline, preferably also –C=all

- Not bulletproof, but very close to it

Use gfortran –O3 –Wall –Wextra –pedantic –ftrapv
plus –ffpe–trap=invalid,zero,overflow
preferably also –std=f08 –fcheck=all

For Intel use ifort –O3 –warn –ansi–alias –fpe0
preferably also –stand=f08 –check all

Can use C/C++ options for stack checking

Other Languages

I mean Python, Java, Matlab etc.

Some errors (e.g. array bounds) usually trapped
Others (e.g. arithmetic) turned into logical errors

Python is good, Matlab not too bad
Perl and Java are truly horrible
Mathematica is somewhere in between

I have little experience with Excel, XML etc.

Debuggers

I don’t use these much, for a variety of reasons
So can’t recommend any particular ones

Serial debuggers can’t handle MPI or OpenMP
Only proper parallel debuggers are commercial
Except possibly gdb etc. on OpenMP code

Theoretically, can be used on core dumps
But far too often just say “No stack”

Use them if you find they save you time

- But don’t rely on them doing so

Memory leaks etc.

C++ does a lot of memory management
Prevents some problems, makes others worse

- Crashes in destructors often mean unrelated bug

Many leak detectors, e.g. gcc/g++ –fsanitize=leak

Valgrind etc. for many kinds of memory problem
Very verbose – external libraries give false positives!
Checking stack or structures is under development
Need Python or Perl to munge output

Checked Languages ⇒ C etc.

For example, Matlab calling Fortran, C or MPI
Some simple errors trapped and diagnosed correctly
Nasty ones often cause calling language to crash
Usually much later or even a glibc memory dump

- Overwriting bugs (obviously)
- Returning bad pointers or structures
- Getting the use count handling wrong
- Calling API functions inappropriately
- And so on ....

⇒ Use the above techniques to minimise these